CLIMATIC ACCIDENTS
IN
LANDSCAPE-MAKING

PRINTED IN NEW ZEALAND

LAKE BROWNE, A ROCK-BASIN LAKE IN A DEEP CIRQUE HOLLOWED OUT OF A SUMMIT PLATEAU ABOUT 4000 FEET IN ELEVATION; IT "HANGS" ABOVE THE FIORD WALL OF DOUBTFUL SOUND, NEW ZEALAND. THE FIORD IN THE BACKGROUND IS DAGGS SOUND.

V. C. Browne, photo.

CLIMATIC ACCIDENTS

IN LANDSCAPE MAKING

A SEQUEL TO

"LANDSCAPE AS DEVELOPED BY THE PROCESSES OF NORMAL EROSION"

by

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SECOND PRINTING

JOHN WILEY & SONS, INC.
440 FOURTH AVENUE
NEW YORK 16, N.Y., U.S.A.

PRINTED IN NEW ZEALAND

The most important accidents are climatic and volcanic. Climatic accidents include changes from humid to arid, and from cooler to warmer conditions, independent of the normal climatic change due to loss of relief from youth to old age.

W. M. DAVIS

Preface

THE SUBJECT matter of this book follows in natural sequence that of *Landscape*,[1] to which in a sense it is a sequel. Any elementary work on geomorphology, however, or the treatment of landforms as given in textbooks of geology, serves as an introduction to the topics here discussed.

Once I believed it possible to compress into a single volume of reasonable size a fairly comprehensive account of all landforms other than those developed by rain-and-river erosion in humid climates. *Landscape* and its sequel were to furnish a textbook of geomorphology. Climatic accidents and their results have demanded a volume to themselves, however.

Few of the many problems touched upon may be regarded as solved; and discussion continues. At the time of writing these words I have before me as yet only the first instalment of A. D. Howard's study of pediment passes in the *Journal of Geomorphology*,[2] and a contribution to the study of glacier movement and wastage has also just arrived from Professors Flint and Demorest.[3]

Of the making of new terms there is no end, and in recent years geomorphologists (formerly more cautious) have cast hesitation to the winds. More than ninety per cent of new geomorphic terms are stillborn, and this is especially true of the less euphonious and the more rashly manufactured words; but occasionally, both in those didactic articles which propose new systems of classification and terminology and in those ever welcome essays devoted to analysis of specific problems, a new term emerges from the ruck and recommends itself either as supplying a long-felt want or as clarifying a concept hitherto vague. Of words in the latter category the elegant "pediment" is a shining example. Terms which have appeared since the proofs of this book were passed for printing

[1] Second edition, Whitcombe & Tombs Ltd.

[2] February, 1942.

[3] R. F. Flint and M. Demorest, Glacier Thinning during Deglaciation, *Am. Jour. Sci.*, 240, pp. 29-66, 113-136, 1942.

are "pediplane" as re-defined and "peripediment" as defined by Howard. Both terms crystallise definite ideas, but it is doubtful whether either is really indispensable for descriptive purposes, and both tend unfortunately to cut the ground from under the accepted, and very acceptable, "pediment". If the manufactured term "pediplane" (perhaps with a variant "pediplain") supplants "pediment", "pediplanation" will replace "pedimentation", itself a useful coinage.

Much of the substance of Chapters III, XV, XVIII, XIX, and XXI of this book has already appeared in the *Journal of Geomorphology*, the *Geological Magazine*, and the *Journal of Geology*, and the editors of these journals have permitted the reproduction of some line illustrations. For others I am indebted to the *Geographical Review* and the *Bulletin of the Geological Society of America*.

The American Museum of Natural History, the New York State Museum, and the Geological Surveys of Great Britain and the United States have generously allowed the use of photographs, as have also various other correspondents. Acknowledgments of these are made in credit lines. In a few cases I have found it necessary to use photographs, long in my possession, of which the source is unknown or forgotten. Some of the uncredited photographs are my own work.

C. A. COTTON

Wellington
May 1942

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CLIMATIC ACCIDENTS IN LANDSCAPE-MAKING

Introduction

Since the distinction between "normal" and "special" processes (and their results) was introduced into geomorphology by W. M. Davis, the results of the work of rain and rivers (pluvial and fluvial processes) in landscape-making have come to be very generally accepted as normal. These processes are indeed normal, however, only when they operate in humid climates in the cool temperate zones, producing landscape forms .such as first seriously attracted scientific attention—the forms for which Davis elaborated his theory of the cycle.

The "geographical" or geomorphic cycle—the orderly procession of landscapes succeeding one another in cycle stages of infancy, youth, adolescence, full and late maturity, senescence, and senility of the land surface—requires almost infinite time to run its full course. This cycle, however, may be "interrupted" at any stage by earth movements or by a change in the position of base-level; or the "normal" sequence of events may be varied by the occurrence of an "accident" either volcanic or climatic. After radical changes in configuration have been brought about by vulcanism or by the ravages of the natural forces let loose by climatic change, another "normal" cycle may conceivably be entered upon as a result of either local exhaustion of volcanic energy or a return to the climatic norm.

Besides refrigeration, which introduces glacial erosion, and the climatic swing to aridity, which involves the elimination by desiccation of the base-level control of landscape development, relatively minor changes result in the production of definite landscape types. The onset of semi-arid conditions without eliminating base-level

control emphasises the process of "pedimentation" and all that that implies; and tropical dry and perhaps also equatorial wet climates also involve some important departures from the "normal" course of the cycle.

In terms of geomorphology, as well as of historical geology, the Pleistocene glacial period has been but an episode, and in all but Polar regions the special features imposed on the landscape by intense glacial erosion are now almost entirely relict; and the same may be true of climatic changes due to shifting of the subtropical high-pressure belts so far as such changes are recorded in the features of present-day landscapes. Just as one may base conclusions on observations made on glaciers, however, in a few selected localities where they still linger and continue the work of landscape sculpture, so also it may be possible to collate the results of studies of dry climate processes and landscapes that have been made *in situ* and to arrive eventually at a conception of the somewhat various landscape cycles controlled by various climatic conditions. In the present state of geomorphic theory it is not possible to do more than make suggestions to this end, and, while some such suggestions carry the weight of authority, others that are embodied in this volume are tentative and are offered with diffidence.

SECTION I

DRY AND DRY-SEASONAL CLIMATIC LANDSCAPE TYPES

CHAPTER I

Aeolian Erosion

It is usual to begin any description of desert landforms with an account of the activity of wind as an eroding agent, and it has often been expressed and more often implied that many of the conspicuous features of desert landscapes (even mountains and mountain ranges) result from aeolian circumdenudation or are at least wind-shaped.[1]

In the light of modern studies of desert erosion it is believed now, however, that few if any major relief forms owe their origin or shape to wind scour and that the sculpture by wind of features even of minor detail in the landscape is rare and exceptional.

The undercutting of certain escarpments has been regarded as due to the activity of wind, especially where these isolate steep-sided buttes in rocks of horizontal structure, such as have been described as *Zeugenberge* in the Sahara by Walther[2] and have been observed by Cross[3] in Dry Valley, Utah; they are characterised by complete

[1] J. Walther, Die Denudation in der Wüste, *Abh. K. Säch. Gesells. Wiss.*, 16, 1890; *Das Gesetz der Wüstenbildung*, 1900 (also 1912 and 1924); C. R. Keyes, Rock Floors of Intermont Plains of the Arid Region, *Bull. Geol. Soc. Am.*, 19, pp. 63-92, 1908; Deflative Scheme of the Geographic Cycle in an Arid Climate, *ibid.*, 23, pp. 537-62, 1912; W. H. Hobbs, The Erosional and Degradational Processes of Deserts with Especial Reference to the Origin of Desert Depressions, *Ann. Ass. Am. Geog.*, 7, pp. 25-60, 1917.

[2] *Loc. cit.* (1).

[3] W. Cross, Wind Erosion in the Plateau Country, *Bull. Geol. Soc. Am.*, 19, pp. 53-62, 1908.

absence of talus at the base (Fig. 1). Such residuals owe perhaps a part of the steepening of their escarpment slopes to the removal of talus by wind, but in general this may take place only after the action of weathering has already reduced fallen rock debris to a fine grade of waste and most even of this material may be removed

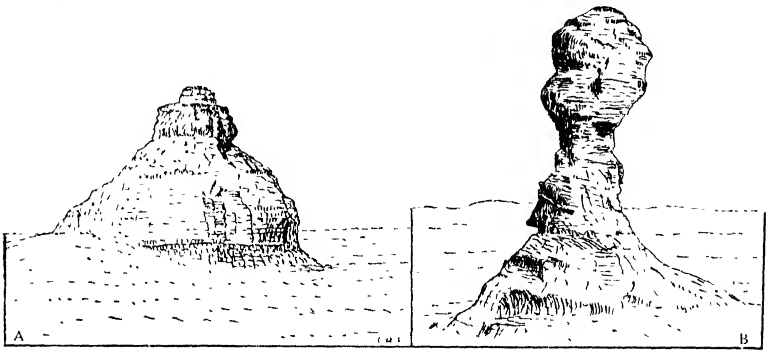

Fig. 1. A, a butte in Dry Valley, Utah, for the shaping of which the agency of wind has been suggested (after Cross); B, a sandstone "monument," Red Buttes, Wyoming, which is regarded as shaped by normal erosion (after Darton).

from the escarpment bases by rain-wash. The sheetfloods and ephemeral torrential streams, indeed, which are formed during desert cloudbursts move vast quantities of fine waste and in some places also some coarser rubble and even large fallen blocks, as has been observed by Walther in Africa.

Deflation

The process of "deflation"[4] includes the removal of sand and dust by wind generally after it has already been loosened by some means, but the coarser material (sand) remains in the desert, though it travels perhaps far to leeward of its source. Weathering and the comminution of rock chips and sand as the sandy waste is driven to and fro by the winds of the desert produce much dust, and, after sojourning long in the desert dust particles some time or another are whirled high enough by storms to be carried by the wind beyond the desert boundaries. This dust-removal, allied to (a part of) the process of deflation, has been termed by Davis

[4] J. Walther, *loc. cit.* (1890), p. 38; (1912), p. 166.

"exportation." It is the only process by means of which it is possible to account for any continuous lowering of the desert land surface as a whole or of differential hollowing out of certain parts of it, of which evidence has been found. Thus Berkey and Morris[5] explain the excavation of large basins without drainage outlets, which they call "P'ang Kiang hollows," in Mongolia (Chapter II). As recorded by Berkey and Morris:

> Almost every day while we were camped in such a hollow we saw "whirling pillars" of dust racing across its dry floor. During violent windstorms the air was dark with flying dust and sand and the sun was dim and red. Dust veils hung in the air for days after the biggest windstorms. . . . No doubt some of the finer material is exported to great distances, even beyond the rim of the Gobi.[6]

The deflation process seems to account also for the excavation of somewhat similar oasis depressions in the Libyan Desert[7] and for long furrows aligned on synclines of the more easily disintegrated rocks of the region in the Namib Desert of South-west Africa.[8]

Corrasion by Wind

Actual corrasion by wind-driven sand grains (the natural sand-blast), apart from the obvious part it plays in the production of desert dust, is an actual process of which evidence is available in the facets worn on pebbles which lie in the course of the wind-driven sand both in deserts and where dry sand is driven by the winds of more humid regions in river beds and in coastal districts fringed by sand beaches.

The sand-blast action is obviously capable of attacking and wearing away larger blocks of rock also and even the bases of cliffs along which the sand is driven; and this is known to be a process actually in operation. Steep rock surfaces exposed to the sand-blast become polished and, in the case of rocks that are only

[5] C. P. Berkey and F. K. Morris, *Geology of Mongolia*, Am. Mus. Nat. Hist. N.Y., 1927.

[6] *Loc. cit.* (5), pp. 336-7.

[7] W. H. Hobbs, *loc. cit.* (1); J. Ball, Problems of the Libyan Desert, *Geog. Jour.*, 70, p. 33, 1927.

[8] E. Kaiser, Studien während des Krieges in Südwestafrika, *Zeits. Deutsch. Geol. Ges.*, 72, pp. 50-76, 1920; Bericht über geologische Studien während des Krieges in Südwestafrika, *Abh. Giessener Hochschulgesells.*, 2, pp. 1-58, 1920.

moderately hard, undercut (Pl. I, 1) or grooved (Pl. I, 2) in the direction of prevailing winds. As coarse sand capable of vigorous abrasion is carried along only quite close to the ground, sand-blast activity is concentrated at low levels and traces of it are rarely found at a height of more than two or three feet. Even close to the ground they are seen only in the windiest and sandiest situations; and, in the case of those cliffs of rock that are polished and undercut at the base by the natural sand-blast it rarely appears from the configuration of the landscape that the process of aeolian abrasion has been the cause chiefly responsible for the development or steepening of the cliffs.

As an illustration of the restricted localisation of aeolian abrasion to certain favourable situations it has been pointed out that crystals of the very soft mineral selenite (gypsum) commonly lie about on the surface of dried lake-floor deposits even in the vicinity of features which have been thought, but perhaps mistakenly, to have been carved by the sand-blast. Though highly susceptible to abrasion by sand, as has been proved, if it were necessary, by laboratory tests, these outdoor crystals remain bright and glistening, so as to indicate a "general absence of effective wind scour."[9]

The work of the natural sand-blast, or "abrasion," must be distinguished, as is carefully done by Blackwelder,[10] from deflation, which is merely the removal of already loosened particles. As redefined by Hobbs,[11] deflation is "the wear of wind unaided by cutting tools."

Abrasion is a process that has been credited with probably more than its just share in the steepening of scarps—especially of structural escarpments—in deserts. Occasionally low escarpments are found to overhang as a result of rather obvious wind scour at the base; but such undercutting produces only small-scale features, and these are developed as a result of abrasion only of rock materials either originally weak or decayed by some process of weathering. Such a process may be normal chemical weathering of surfaces moistened occasionally perhaps by seepage of ground water. It is suggested

[9] K. Bryan, Selenite Fragments or Crystals as Criteria of Wind Action, *Science*, 72, pp. 169-70, 1930.

[10] E. Blackwelder, Yardangs, *Bull. Geol. Soc. Am.*, 45, pp. 159-66, 1933.

[11] W. H. Hobbs, *Earth Features and their Meaning*, p. 204, 1912.

also that superficial disintegration may result from wedging effects due to repeated crystallisation of salt in the interstices of the rock.[12]

Rapid abrasion is obviously in progress only on outcrops of very soft materials such as dried lake-bed clays and similar imperfectly indurated sands and silts.

YARDANGS

Almost the only well-authenticated relief forms attributed solely to wind scour are some elongated U-profile furrows separating ridges which are generally sharp-edged and are termed "yardangs"[13] (Pl. II, 1). There is a certain resemblance in cross-sectional profile between yardangs and the intercatenary ridges between closely spaced glacial troughs (Fig. 107), though on a very different scale. Occasional variants of the yardang form are rounded, streamlined, and fantastically shaped small features—the "sphinx rocks" of Walther.[14] All are elongated in the prevailing wind direction. Yardangs and related forms have been carved only from the least resistant of materials and are only minor features of the landscape producing a relief ranging from a few inches to 25 feet. The sphinx rock figured in Plate II, 1, is only 7 feet high. Typical yardangs have closely spaced consequent gullies cut by rain in the soft material of their steep sides (Pl. II, 1), and the fact that these do not extend quite down to the floor of the wind-scoured "yardang trough" indicates progressive recent deepening of this. The chief interest afforded by yardangs lies in the fact that their occasional presence serves to show up by contrast the absence of large features and, except rarely, even of small-scale features at all resembling them on the outcrops of hard rocks. It is thus indicated that "wind *abrasion* is not a factor of much importance in fashioning the larger topographic features of the desert."[15] Residual mesas and buttes in lake-floor and playa-floor

[12] J. T. Jutson, The Influence of Salts in Rock Weathering in Sub-arid Western Australia, *Proc. Roy. Soc. Victoria,* 30, pp. 165-172, 1918.

[13] Sven Hedin, *Central Asia and Tibet,* Vol. 1, p. 350, 1903; E. Blackwelder, Yardangs, *Bull. Geol. Soc. Am.,* 45, pp. 159-166, 1934.

[14] *Loc. cit.* (1).

[15] E. Blackwelder, *loc. cit.* (10), p. 164. Contrast Passarge's theory of inselberg development (see p. 24; also Chapter VIII).

clays[16] (Pl. II, 2) may be of similar origin to yardangs, but may be shaped, on the other hand, by rain-wash and running water after a lowering of the adjacent local base-level by deflation has made this possible. They are of considerable interest as affording proof of the lowering of base-level by wind exportation of dust from desert basins.

Pedestal Rocks

Among minor features of the landscape in explanation of which aeolian abrasion has been invoked "monuments" (a term not strictly defined) and "pedestal rocks" figure conspicuously.[17] The latter are residual columns of soft material isolated by erosion and capped by masses of hard rock which are generally remnants of eroded horizontal formations. Deflation may have a minor share in their formation in some cases, but the theory that they owe their shape to undercutting by wind scour has been abandoned in most cases in favour of a superficial crumbling of the weak rock of the pedestal as it is affected by dry weathering, a process which Bryan terms "differential sapping." The fact that pedestal rocks are more abundant in arid than in humid regions

> is probably due not so much to differences in the nature of the processes of weathering and erosion as in their rate, for in humid regions the formation of soil by chemical weathering and the growth of vegetation inhibit the formation of pedestal rocks in favourable places or rapidly destroy them when formed. (Bryan).

Cavernous Weathering

The process of differential sapping results also in various manifestations of cavernous weathering, producing the small and large recesses in rock faces for which Penck has adopted the Corsican term "tafoni."[18] Though they appear most conspicuously

[16] "Aeolian mesas, made of pink and greenish clay and from thirty to sixty feet high" on the former floor of the great lake Lop-nor, in Central Asia, are described by E. Huntington (*The Pulse of Asia,* p. 254, 1907); and there are similar but smaller features (mesas capped by a resistant gypsum layer) on the extensive playa-floor of Danby Dry Lake, California (E. Blackwelder, The Lowering of Playas by Deflation, *Am. Jour. Sci.,* 21, pp. 140-144, 1931).

[17] K. Bryan, Pedestal Rocks formed by Differential Erosion, *U.S. Geol. Surv. Bull.,* 790-A, pp. 1-15, 1926.

[18] A. Penck, *Morphologie der Erdoberfläche,* Vol. 1, p. 214, 1894.

in dry regions, features resulting from cavernous weathering are also common in seaside cliffs[19] (Pl. III, 1 and 2). By this process numerous rock shelters (termed also "alcoves"[20] and "niches"[21]) and even natural bridges[22] have been formed in homogeneous rocks of various kinds, including massive sandstones and granites,[23] volcanic lavas, and agglomerate.

The granular products of rock-decay and disintegration are in part removed from the recesses by wind, but commonly also rain-wash co-operates with it. Rarely or never are positive signs of sand-blasting found in association with typical tafoni. According to the view of Blackwelder, the rock is disintegrated and thus prepared for removal largely by chemical weathering, but recent investigators of Corsican granite tafoni continue to regard the process as almost entirely physical.[24]

Heterogeneous rocks in outcrops exposed to wind-driven sand may have the softer parts etched out in patterns by the sand-blast;[25] but "stone-lattice" and "honeycomb-weathering" patterns observed on bare-rock surfaces (Pl. III, 3), which are sometimes cited in this connection, cannot be ascribed to abrasion. Wind does, no doubt, remove loosened grains from the recesses as they develop in this weathering process in some cases between partitions simultaneously hardened by mineral matter deposited from solutions brought to the surface by capillarity; but the fact that patterns are left standing in relief on the weathered surface may be taken as evidence of the feebleness rather than strength of the process of aeolian abrasion in situations where this type of weathering is in evidence. It is found not only in deserts, but occurs commonly also in some humid regions, though necessarily restricted to bare-rock outcrops, which are much rarer under humid conditions than in deserts. Its common occurrence at the seashore has suggested that disintegra-

[19] J. A. Bartrum, Honeycomb Weathering of Rocks near the Shoreline, *N.Z. Jour. Sci. & Tech.*, 18, pp. 593-600, 1936.

[20] W. Cross, *loc. cit.* (3).

[21] K. Bryan, The Papago Country, Arizona, *U.S. Geol. Surv. W-S. Paper*, 499, pp. 90-93, 1925.

[22] H. E. Gregory, Geology of the Navajo Country, *U.S. Geol. Surv. Prof. Pap.*, 93, pp. 133-4, 1917.

[23] E. Blackwelder, Cavernous Rock Surfaces of the Desert, *Am. Jour. Sci.*, 17, pp. 393-9, 1929.

[24] Kvelberg and Popoff (Review by R. H. Rastall, *Geol. Mag.*, 76, p. 142, 1939).

[25] W. H. Hobbs, *loc. cit.* (1).

tion of the rock surface and especially the deeper excavation of early-formed pits is assisted by repeated crystallisation of salt in minute interstices of the rock.[26]

In New Zealand this is the process chiefly responsible for disintegration of beach boulders and rock stacks in situations where these are no longer subject to marine abrasion. Probably the optimum for the process is found in a climate where freeze-and-thaw effects are rarely felt and where disintegration by insolation is minimised by small diurnal range of temperature.

Desert Pavement and Lag Gravel

Where land surfaces are somewhat lowered—though it may be with little or no modification of form—by the action of wind which removes fine material, coarser fragments of rock, either the residuals in a weathered soil or the pebbles and boulders of a conglomerate or gravel, remain and accumulate as "lag gravel." This forms in some cases a "boulder pavement," which is very resistant to further deflation and, indeed, to most kinds of surface erosion. It is sometimes for this reason called "desert armour."[27] Such protective rock fragments are closely strewn over the surfaces of the "hamadas" (stony deserts) of the Sahara and are crusted with an enamel-like "desert varnish" of iron and manganese oxides developed on the surface as mineral-bearing solutions exude.[28] This is the nature also of the "gibbers" of the Australian stony deserts termed "gibber plains."

[26] J. A. Bartrum, *loc. cit.* (19); compare J. T. Jutson, *loc. cit.*

[27] Berkey and Morris, *loc. cit.* (5), p. 326.

[28] J. Walther, *loc. cit.* (1).

CHAPTER II

The Cycle of Arid Erosion

A CHANGE to aridity is one of the "climatic accidents" which Davis[1] has recognised as necessarily introducing such variations in erosional processes and routine as must bring a cycle of "normal" erosion to a premature close. After such a change the young, mature, or old landscape developed under the former conditions will furnish initial forms for transformation into an arid-desert landscape.

Aridity, like glaciation (the result of another climatic accident), may be a passing phase,[2] but in some regions arid conditions have long ruled, and so it is justifiable to attempt to derive the landscape forms of arid deserts under the prevailing climatic conditions by a slow process of development from initial tectonic forms such as elsewhere introduce a cycle of "normal," or humid, erosion.

Just as is the case in regions with humid climates, the agent chiefly responsible for the development of the major features of most desert landscapes by erosional sculpture and by transportation and deposition of waste is flowing water, which acts in association with the disintegration by weathering of the material of slopes and of all salient features, and with the downhill gravitational transfer of the resulting debris. As has been noted in Chapter I, only some minor features of the desert surface can be explained as resulting directly from the effects of erosion by wind.

SHEETFLOODS

Desert rains are infrequent, but no desert is rainless. After the rare and local "cloudbursts" in hot deserts of the subtropical belts the infrequent but locally abundant precipitation runs off mainly as ephemeral "streamfloods," as Davis has called them rather than "streams," which take the place of the more permanent streams and rivers of more humid climates and run wherever definite channels are present to guide and contain them. Though evanescent

[1] W. M. Davis, Physical Geography as a University Study, *Jour. Geol.*, 2, pp. 66-100, 1894; Complications of the Geographical Cycle, *Rep. VIII Internat. Geog. Cong.*, p. 159, Washington: 1905.

[2] W. M. Davis, *loc. cit.* (1) (1905), p. 159.

and infrequent, these floods move vast quantities of rock debris to lower levels. There are also "sheetfloods," so named and described by McGee,[3] which, though rarely seen in action, have left abundant traces of their passage, as Davis has described,[4] down many broad smooth slopes so closely associated with braided channels of sheet-flood flow (Chapter V) that they seem normally adjusted to this form of run-off.

At a far advanced stage of the cycle of arid erosion wind must assume great importance as a transporting and especially as an "exporting" agent, becoming then the chief factor in the general lowering of the land surface, but in earlier stages of desert landscape development water transport of rock debris must be judged to be quantitatively dominant.

Local Base-levels

In a general way theories of arid-desert erosion are based on analogy with water work in humid climates; but it is going too far in this direction to attempt, as has sometimes been done, to find identity or complete homology between all forms developed by arid (as well as semi-arid) erosion and those of the normal cycle. One important distinction between the conditions of development of normal and desert landscapes is the relatively minor part played in the latter by the general base-level as a level towards which the surface tends to be worn down, though local base-levels apparently exercise a strict control on all water work in deserts, as elsewhere. In a truly arid region there are no streams comparable to those which in humid regions join forces to form rivers flowing to the sea. Instead, ephemeral streamfloods and sheetfloods of the desert rapidly dwindle, deposit the waste they are carrying, and sink into the alluvium-covered ground. At most the diminished streams may occasionally flow a little farther and discharge into lakes occupying the lowest parts of intermont or larger inland basins. Evaporation, which removes a volume of water proportional to the free surface, prevents such lakes from growing large enough to spill over and form integrated systems of drainage. Their waters become concentrated solutions of salts, and generally in dry seasons

[3] W. J. McGee, Sheetflood Erosion, *Bull. Geol. Soc. Am.*, 8, pp. 87-112, 1897.
[4] W. M. Davis, Sheetfloods and Steamfloods, *Bull. Geol. Soc. Am.*, 49, pp. 1337-1416, 1938.

they dry up altogether, leaving plains of saline silt. These shallow, inconstant salt lakes are "playas." Each forms a temporary base-level for the basin on the floor of which it lies, but this is a base-level that rises as waste accumulates in the basin; and the base-levels in separate basins are entirely independent of one another.

Through-flowing rivers, like the Nile, which may rise in humid regions and flow through deserts, stabilise the local base-levels therein, though perhaps only in narrow strips. They also export waste, and, if vigorous and full-bodied, may be capable of preventing such local accumulation of waste as might cause a rise of local base-level. The Nile, it may be noted, where it flows through Egypt is an intruder which has entered the tectonic desert trough now forming its lower valley rather recently. Prior to that event the processes of desert erosion worked in Egypt without the interference of a through-flowing river.[5]

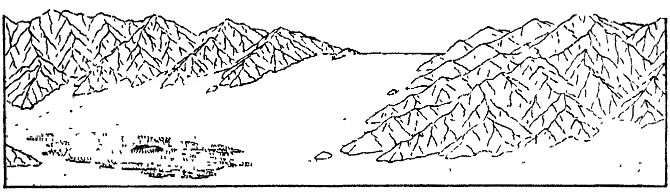

Fig. 2. Davis's diagram of "generalised features of the Mohave Desert."

Davis's Cycle of Arid Erosion

For the cycle of erosion under arid conditions Davis[6] has assumed as typical initial forms those of a landscape of strong large-scale tectonic relief—that is to say, a mountainous desert—like the Californian and Nevadan region of recent fault-block deformation, or that of western Mongolia. There are no out-flowing rivers in such a region, but slopes and drainage courses lead down into separate tectonic basins, in the lowest part of each of which a playa is formed (Fig. 2), fed by water much of which travels most of its way underground after some coarse alluvium

[5] A. C. Lawson, The Valley of the Nile, *Univ. of Calif. Chronicle*, 29, pp. 235-59, 1927.

[6] W. M. Davis, The Geographical Cycle in an Arid Climate, *Jour. Geol.*, 13, pp. 381-407, 1905 (reprinted in *Geographical Essays*, pp. 296-322, 1909).

derived from the waste of the surrounding mountains has accumulated in the basin.

The level of the playa is a local base-level that controls both the degradation of the surrounding uplands or mountains and the slopes of deposition and of transportation leading down to the playa, whether such transportation be by streamfloods or sheet-floods. This is a rising base-level in early stages of the cycle of desert landscape-development, as the level of the whole basin floor, including the playa, is raised by deposition of the debris derived by erosion from the surrounding heights. Proof of such basin-floor aggradation and progressive rise of local base-levels is afforded by (historically) ancient and recent changes in the lakes on the floor of the vast Tarim Basin of centripetal drainage in Central Asia, which has an area of some half-million square miles. Fifteen hundred years ago the infilling with waste of the playa lake Lop-nor, in the eastern, deepest part of the basin, resulted in such instability that it caused diversion of the main inflowing stream with the formation of a new lake, Kara-koshun, on another part of the basin floor. Thus Lop-nor, deprived of its water-supply, dried up and became a salt-covered desert plain. Very recently, however, the tables have been turned, for, owing to progressive building up of the floor of Kara-koshun and of the aggraded plain sloping towards it and controlled by its local base-level, another diversion of the chief inflowing stream (Kum-daria) has taken place, and the Lop-nor playa has again become a shallow lake.[7]

In certain cases adjoining basins may become linked together by spilling-over of waste (along with intermittent water streams) through a gap, after one has been filled to the gap level, or by capture of the drainage of a higher basin by a ravine working headward from a lower one. After this has occurred the base-level of the lower of two basins so joined continues to rise, but some erosion and dissection of the floor of the higher basin may now take place, as it has exchanged its own base-level for that of its lower neighbour. Thus, early in the cycle complications may be introduced, such as ravining and terracing of basin-floors, exemplified in some of the desert basins of south-eastern California.

[7] Sven Hedin, *The Wandering Lake*, London: 1939.

In addition to local independence of base-levels and predominantly rising base-levels other distinguishing features of arid landscape development pointed out by Davis in his classic sketch of thė arid cycle[8] are as follows: Plant growth being very scanty, the desert vegetation affords the surface little or no protection; there is little chemical weathering, but rock-breaking by physical weathering predominates;[9] and the streams are intermittent, at least "at their upper and their lower ends."

Still another characteristic of desert land surfaces as distinguished from those in humid climates is that "antecedent rivers persisting from a previous cycle against the deformations by which the new cycle is introduced must be rare, because such rivers should be large, and large rivers are unusual in an arid region. Consequent drainage must prevail." (Davis). This is almost equally true of semi-arid regions (Chapter III). Large through-flowing rivers of all kinds must be treated as exceptional in both semi-arid and arid regions. Where they are present—for example, the Colorado and the lower Nile, neither of which is probably antecedent—they introduce special features into desert landscapes related to their local base-levels, but only in rather narrow strips that border them.

At the early stage termed "youth" in Davis's scheme of the arid cycle streams are actively dissecting uplands and highlands (Pl. IV, 1 and 2), and abundant waste is being carried into basins, to be deposited there mainly as bahadas more or less homologous with those of more humid regions, and as lake deposits. In contrast with the normal, or "humid," cycle, youth is here a stage of diminishing relief, for the ground level in the basins is being raised by accumulation. The great desert basin of Chile and smaller basins in south-eastern California illustrate this stage (Pl. IV, 1).

Upland and highland areas become maturely dissected, and "maturity" of the desert landscape as a whole is marked by some integration of formerly separate drainage systems, where waste

[8] *Loc. cit.* (6).

[9] This pronouncement of Davis he modified later by recognising that "subsoil weathering" by chemical processes is an important preliminary stage in the bouldery disintegration of granite surfaces in deserts. "This is proved by the occurrence of disintegrated rock well below the surface, as shown in artificial cuts. . . Thus prepared, the boulders are laid bare by the removal of the soil from above, around, and beneath them by wash and creep." (W. M. Davis, Sheetfloods and Streamfloods, *Bull. Geol. Soc. Am.*, 49, p. 1360, 1938.)

(and water) spill over and stream from basin to basin, or where the drainage of higher basins has been captured. On the borders of an arid region transitional to semi-aridity integration at maturity will result in transfer of some basins of former internal (centripetal) drainage to the valley systems of rivers that flow to the sea, with the introduction in such districts of control by the general base-level.[10]

Meanwhile "the obliteration of the uplands, the development of graded piedmont slopes, and the aggradation of the chief basins will be more and more extensive. [Figs. 2 and 3, B]. The higher parts of the piedmont slopes may be rock floors thinly and irregularly veneered with waste" (Fig. 3, C). The "piedmont

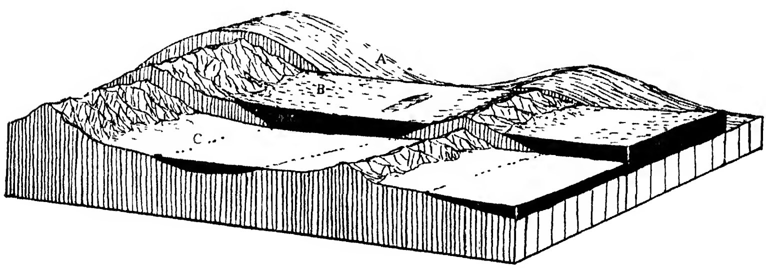

Fig. 3. Davis's arid cycle in a mountainous desert. A, initial tectonic form; B, youth; C, maturity. (Based on a diagram by Davis.)

slopes" here referred to include degraded "bahadas" and "pediments" as usually defined (p. 34). Elements of the desert landscape are now

> large rock-floored plains [pediments] sloping towards large waste-floored plains [bahadas]; the plains will be interrupted only where parts of the initial highlands and masses of unusually resistant rocks here and there survive as isolated residual mountains. . . . In so far as the plains are rock-floored they will truncate the rocks without regard to their structure. (Davis).

As the residual mountains dwindle and are destroyed by desert erosion, "old age" of the landscape approaches, though it still has considerable undulating relief and piedmont slopes still retain in most parts a drainage pattern of "washes" (dry streamflood courses)

[10] W. M. Davis, *Die erklärende Beschreibung der Landformen,* p. 372, 1912; Kirk Bryan, The Formation of Pediments, *Rep. XVI Internat. Geol. Cong.,* p. 6, 1935.

traversed by streamfloods at infrequent intervals—a pattern that may differ little as yet from that of maturity, though lowering of relief (if primitive relief has been strong) must have reduced rainfall and, therefore, the volumes of floods.

The Desert Plain of Mongolia

Large-scale examples of early to late mature landscapes in the arid cycle are found among the ranges and secondary basins of the western part of the great Mongolian basin, as it has been described by Berkey and Morris; while their description of the "Gobi erosion plane," an undulating rock floor which constitutes a great part of the Gobi Desert in the eastern and southern parts of the same great basin, places this landscape surface in the category of old-age forms.[11] If it has always been divorced from the control of an external base-level, the surface must be related to arid rather than to merely semi-arid erosion. Its depth of excavation has been controlled undoubtedly, in that case, by former levels of the ground water under it, just as the depth to which it is subject to rejuvenation by wind excavation of newer hollows is controlled by the existing ground-water level. The undulating surface slopes down into several basins with centripetal drainage, but in these there is little accumulation of gravels (though the surface of the plain has generally a gravel veneer). The absence of thick gravels and lake beds in the basins must be explained as a result of the long-continued exportation of dust by wind. Possibly this exportation of dust from the very extensive plains has gone on sufficiently rapidly throughout their history to prevent thick accumulation of coarser debris in the basins at all stages of their development. The smoothing of the plains is attributed by Berkey and Morris, however, to the activity of flowing water—a sheetflood effect—though possibly much of this activity may be ascribed to more abundant and voluminous sheet-floods under a Pleistocene climate moister than that of the present day.

In basins *formerly* existing in the same region thick bahada and lake-bed deposits accumulated, but these terrestrial formations (of Cretaceous and Tertiary ages) have undergone tilting and

[11] C. P. Berkey and F. K. Morris *Geology of Mongolia,* Am. Mus. Nat. Hist., New York: 1927.

folding, and now make up a great part of the terrain underlying the modern desert plain.

The Libyan Desert

In the Libyan Desert there is a vast level surface of erosion closely similar to the "Gobi erosion plane" of Mongolia.[12] The erosion plain has been termed a "sand sheet," as it is overspread by a thin sheet of sandy debris which is stirred up by storms, and also a "desert peneplain."

Throughout North Africa the climate of a not-far-distant past epoch was somewhat moister than that now prevailing, and abundant signs of former human occupation in the heart of the Libyan Desert indicate that former conditions differed considerably from the intense aridity of to-day. With diminished activity of running water resulting from the reduction of concentrated precipitation to a cloudburst perhaps once in seven years erosion is now slowed down almost to a standstill, and the landscape is to some extent relict.

Under the present dry conditions, and undoubtedly more vigorously under the heavier precipitation of the past, dissection by numerous ravines ("wadis") is and has been in progress on the margin of the plateau that forms the core of the desert, while around this core erosion has developed a fringing plain which may be described as made up of very flat coalescing pediments. Between the youthfully dissected plateau-margin (Fig. 4) and the surrounding plain there is a transitional belt of mature dissection, where branching extensions of the plain stretch as embayments among and beyond isolated buttes (Fig. 5) at the fringe of the mesa-like upland plateau, and these tentacles of the plain reach up into the upland along the flat floors of the dissecting "wadis" (Fig. 4). The terrain consists of horizontally bedded sandstones generally with a quartzite capping layer which is an escarpment-maker, and the average relief at the plateau margin is round about 1000 feet.

The rock floor of the "desert peneplain" and its tentacle-like extensions into the upland is nowhere deeply buried under alluvial drift, bahadas are of insignificant extent, and "concealed" but not

[12] The landscapes of the Libyan Desert have been described by R. F. Peel in Bagnold and others, An Expedition to the Gilf Kebir . . . , *Geog. Jour.*, 93, pp. 281-313, 1939; also Denudation Landforms of the Central Libyan Desert, *Jour. Geomorph.*, 4, pp. 3-23, 1941.

deeply buried pediments are ubiquitous. These emerge at the bases of cliffs that have been developed by back-wearing weathering processes (Chapters IV-VI) along escarpments of the mesa-like upland, around isolated buttes, and along the side cliffs of every branching "wadi" embayment. The scarp-foot has been somewhat buried by accumulating talus, however, and in the current episode of

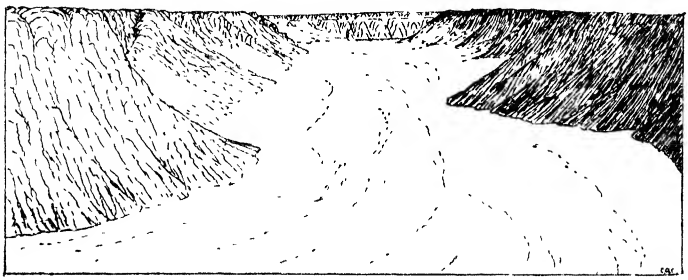

Fig. 4. A youthful stage of insequent dissection at the margin of the Gilf Kebir plateau of Nubian sandstone by flat-floored "wadis." (Drawn from a photograph.)

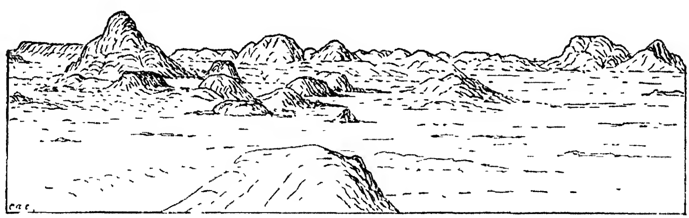

Fig. 5. Maturely dissected horizontally bedded Nubian sandstone area reduced to buttes, north-east of Gilf Kebir, Libyan Desert. (Drawn from a photograph.)

extreme aridity wind is (locally, at least) powerless to abrade and remove this talus.[13] The alluvial wash on wadi-floors is patterned with braided or sheetflood courses, but on the extensive coalescing pediments ("desert peneplain") of the marginal region the loose "sand-sheet" material is now constantly stirred by windstorms and its abrasion produces dust for exportation. The thickness of this sheet is at present sufficient, however, to protect the bedrock beneath it, and such evidence of aeolian abrasion as has been observed is confined to the windward sides of the few residuals of

[13] R. F. Peel, *loc. cit.* (12).

bedrock that still project. It may not be safely inferred that such residuals have been much reduced in number because of the destruction of some by aeolian planation. The process of pedimentation (Chapters IV-VI) under conditions of aridity less severe than those now prevailing has very probably been responsible for the virtual planation that has taken place.

Here, as in eastern Mongolia, there seems to be an example of the pedimentation cycle in a region of relatively small major initial relief (as contrasted with the strong tectonic initial relief in American "mountainous deserts") but with some regional slopes and such a measure of initial relief as has led to dissection of a formerly smooth upland surface by consequent and insequent ravines in an early stage of the cycle. In general the pediment slopes that have been developed are much gentler than those derived by the planation processes from the major relief forms of mountainous deserts, and present few or no prominent fan-like convexities.

In view of the flatness of the plains and of the convincing evidence of very recent climatic changes in North Africa, it is impossible to exclude altogether an alternative hypothesis that the Libyan Desert formerly enjoyed a "savana" climate (Chapter VIII), and that the plains were levelled and the buttes isolated by lateral river planation "when the lifeless yellow plains . . . . were green."[14] The presence of undrained hollows in other parts of the Libyan Desert, which very probably were excavated by wind, and which cannot but have required a long period for their gradual development, is an argument, however, which may be urged against the prevalence even in the Pleistocene period of a climate very much more humid than that of to-day. It can scarcely be assumed that the desert landscape was shaped under conditions other than semi-arid to arid.

Wind-scoured Hollows

Davis, in his original deductive scheme of the arid cycle, assigned an important role to wind scour in a late stage of arid denudation, when, he deduced, it would scoop out hollows. Such hollows would be quickly filled again with debris carried into them by ephemeral streams, and the surface thus again levelled,

[14] Quotation from R. A. Bagnold, *Geog. Jour.*, 93, p. 284, 1939.

but the general effect would be to destroy such integration of drainage systems as had been attained at maturity, substituting highly disintegrated and ever-changing drainage patterns leading always into the latest-formed incipient wind-scoured hollows. "P'ang Kiang" hollows in the Mongolian desert, which Berkey and Morris[15] ascribe to excavation by wind, as they find all other modes of possible origin inadequate, are of the general nature prophesied by Davis, but on an immensely larger scale than he anticipated, being of the order of five miles in diameter and 200 to 400 feet in depth. Moreover, little waste is washed into the hollows from the higher-level floor of the surrounding desert plain. On the contrary, steep scarps that descend to the hollows are sapped back by stream erosion so as to enlarge the area of the excavation, and the resulting debris, after being reduced to dust, is exported by wind. Meanwhile a level desert floor is again developed by stream work, but at a new low level within the depression and without the accumulation of any except local and ephemeral water-laid deposits.

The level of this floor is determined and controlled by the ground-water level just as in the Qattara Depression and oases of the Libyan Desert, to which a similar origin is ascribed (p. 5). It would appear that these large-scale desert hollows can be developed only after a sinking of the ground-water level has taken place.[15a]

In Mongolia some desert hollows are excavated in granite, others in sedimentary formations. The early stages of excavation of a hollow may be due in some cases to enlargement by wind of gullies cut by streams owing to some locally developed warping or other condition. In semi-arid districts of Africa and North America incipient hollows have been formed by deflation of dust derived from areas that have become depleted of vegetation[16] and also from some in which mud is puddled in wet seasons by the tramping and wallowing of large animals. In the Libyan Desert initiation

[15] C. P. Berkey and F. K. Morris, *Geology of Mongolia*, Am. Mus. Nat. Hist., New York, 1927.

[15a] If the ground-water level has risen again recently under the control of a glacio-eustatic movement of sea-level, a desert hollow may contain a lake on its floor, or an extensive marsh like that in the Qattara Depression in the Libyan Desert.

[16] G. K. Gilbert, Lake Basins Created by Wind Erosion, *Jour. Geol.*, 3, pp. 47-9, 1895.

of the oasis hollows afterwards greatly enlarged by erosion and by wind-exportation of fine debris has been ascribed by Hobbs[17] to minor local down-faulting affecting small areas.

Once initiated, such a hollow, if situated where the ground water sinks or has sunk sufficiently deeply to allow of surface desiccation and continued deflation, will be progressively deepened. The scarps that surround a hollow are worn back, however, mainly by headward erosion of consequent gullies formed on them during heavy rains, or by some other activity of water as rill-wash or sheet-wash co-operating with progressive weathering. In horizontal formations in Mongolia the scarps retreat as structural escarpments; and in every case the processes of pedimentation (Chapters IV-VI) are active at the scarp-foot.

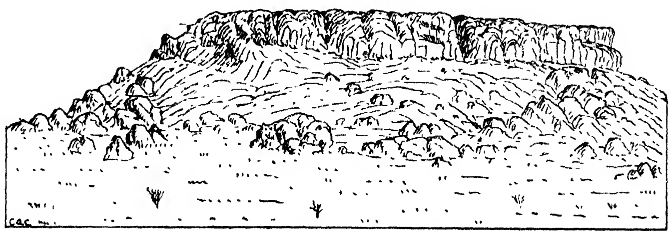

Fig. 6. Breakaway, in granite, bordering a tabular inselberg, Cue, interior of Western Australia. (Drawn from a photograph.)

Somewhat similar lowering of a desert surface of small relief is in progress in Western Australia, but scarps developed in association with it are of smaller height than in the other examples cited. Here also the level of ground water controls the depth of excavation, and very extensive saline "dry-lake," or playa, floors are developed. These are closely analogous with the playas of mountainous deserts, but are separated from retreating scarps only by "pediment" slopes of insignificant breadth. The scarps themselves—termed "breakaways" in Australia—are of no more than 30 to 100 feet in height, and the latter figure is exceptional. Their retreat is largely a back-weathering process and they commonly assume an escarpment profile, because the higher level plain above them, now in course

[17] W. H. Hobbs, The Erosional and Degradational Processes of Deserts with Especial Reference to the Origin of Desert Depressions *Ann. Ass. Am. Geog.* 7, pp. 25-60, 1917.

of destruction, is capped by laterite or surface quartzite related in origin to the calcareous superficial crusts termed "caliche." Isolated remnants of this upland surface form therefore the tabular residuals or "inselbergs" of Australia (Fig. 6).

Some at least of the weathered material removed by the wind from the vicinity of the foot of a breakaway is sand and after being carried across the dry-lake floors accumulates to leeward as dunes. Thus the "lakes" are crowded towards the breakaways, and the whole group of features migrates in the teeth of the prevailing wind.[18] In other parts of the Western Australian interior very much more extensive pediments are developed as breakaways retreat, and these merge into a remarkable level rock floor of vast extent from which it has been observed that fine waste is removed by deflation.[19]

In Australia some two-storied wind-excavated hollows are developing, but none of these are recorded in Mongolia.

In both Mongolian and Australian types of excavation of desert hollows there is direct replacement of one already well-planed rock floor by another at a lower level. To reconcile this with the course of the Davisian arid cycle one would have to suppose those stages elided which are characterised by the presence of extensive bahada and playa deposits. The obvious reason for this elision is that the initial form here is not the mountainous pattern of major tectonic relief forms assumed for the development of the Davisian arid cycle. The present case is to some extent analogous with a normal cycle initiated by uniform uplift of a peneplain; but the proximate cause of excavation is a sinking of the ground-water level due to some ultimate cause outside the immediate problem.

Rather than attempt to correlate the stages of desert erosion by aeolian excavation of hollows with the arid cycle in regions where major initial relief forms are dissected in their youth by running water—a cycle which has more in common with the cycle of semi-arid erosion—it seems better to regard this case

[18] J. T. Jutson, Physiography of Western Australia, *W. A. Geol. Surv. Bull.*, 61, 1914; Erosion and the Resulting Landforms in Sub-arid Western Australia, *Geog. Jour.*, 50, pp. 418-37, 1917.

[19] J. T. Jutson, Sheet-flows or Sheet-floods and their Associated Phenomena . . . , *Am. Jour. Sci.*, 48, pp. 435-9, 1919.

as a separate and distinct cycle in which the large-scale pitting of an upland plain by "P'ang Kiang" hollows is the stage of youth.

Senile Deserts

In advanced old age of the landscape, according to the Davisian cycle theory, very extensive and very nearly level cut-rock plains may be developed; but for this condition of extreme senility of the arid landscape to be attained over a large region of resistant rocks a vastly prolonged period of erosion ("through geological periods"—Davis) may be required, during which aeolian exportation of dust greatly lowers the desert surface.

As the lowering of a desert plain that takes place as a result of wind-exportation of dust is not controlled by the general base-level, it is a theoretical possibility that lowering, provided it be not checked by a close approach to ground water, may continue below sea-level. Few of the known examples of hollows with floors below sea-level can be ascribed to this origin, however. Such cases as the Turfan Basin, Death Valley, and others, where the land surface is below sea-level, though in deserts, clearly owe their descent to rather recent earth movements. But for aridity of climate, of course, these basins would be occupied by lakes instead of exposing dry land on their floors.

The desert surface of Bechuanaland was at one time tentatively accepted by Davis[20] as the product of arid erosion at an advanced old age, but its peculiar features are quite probably capable of other interpretation, and the theory of arid-cycle senility has not been universally adopted for its explanation. In this region remarkable steep-sided residual mountains, generally described as "inselbergs," rise above nearby level rock floors of very wide extent which are only thinly veneered with discontinuous waste. The survival of the "inselbergs" at an advanced old age of desert erosion could be explained only by their location on outcrops of rocks peculiarly resistant to desert weathering. Their survival would have to be taken as proof also that the desert surface is even now being worn down remarkably rapidly; for the residuals are not immune from weathering, and even if they were composed, as has

[20] Following Passarge (see Chapter VIII), who allowed the whole Mesozoic era for the wearing down of the desert plains of Bechuanaland by aeolian erosion.

sometimes been claimed, of rocks more resistant than those underlying the surrounding plains they would gradually crumble away and disappear if the lowering of the level of the surrounding plains were to cease.[21]

Among the extensive senile surfaces or "peneplains" referable to ancient cycles that have been uplifted and dissected and are now recognised in plateau remnants in various parts of the world there are some for which an origin as peneplains of arid-desert erosion has been suggested. It would be rash, however, to attempt in the case of such ancient and imperfectly preserved surfaces to distinguish between the effects of erosion under arid and semi-arid conditions, and the distinction from normal peneplains is generally speculative. Such may be the origin of the summit peneplain of Mongolia, and possibly of the "Tertiary" peneplain of Arizona, which is now trenched by the Colorado canyon, as well as of the "Powell" surface (so termed by Davis), which is traced on the summits of block mountains in the Great Basin of North America. Pre-Triassic arid conditions, it has been also suggested, may have been the cause of the almost perfect planation of the surface now exposed in Wales as summit remnants.[22]

[21] Compare Willis's theory of the survival of "inselbergs" (B. Willis, *East African Plateaus and Rift Valleys,* pp. 119, 127, Carnegie Inst., Washington, 1936). The theory is outlined in Chapter VII.

[22] O. T. Jones, Presidential Address Section C, *Rep. Brit. Assn. Bristol,* 1930.

CHAPTER III

The Landscape Cycle under Semi-arid Conditions

IN attempting to differentiate the landscapes of semi-arid from those of arid regions it is difficult to draw the line between aridity and semi-aridity, just as it is difficult to differentiate between humid and semi-arid climates as they affect the development of landscape forms. No hard and fast divisions based on rainfall figures can be adopted. Evaporation, in part controlled by temperature, and the seasonal distribution of rainfall are also important factors.

> The rainfall regime is divisible [according to Bryan] into the episodic and the periodic. In the episodic type rain falls in storms that are highly variable in intensity and are scattered through the year; in the periodic type precipitation is concentrated in one season, either summer or winter. In areas having the periodic type vegetation is adjusted to the wet season, and a relatively greater vegetative cover is possible with low rainfall. The Mediterranean region and California have the periodic type of rainfall, with winter maximum and mild temperatures. Thus in many sub-areas the land forms under mean and annual rainfalls of 15 to 20 inches are very similar to those of humid regions, although the soils . . . . are quite like those of other arid regions. The episodic rainfall, because of its variability in time throughout the year, is less effective in promoting growth, and the vegetative cover may be so scant with rainfalls of 5 to 7 inches that geomorphologically the region is essentially a desert. Episodic rainfall as high as 15 to 20 inches may produce steppe conditions. . . . In general the warmer areas have a relatively scantier vegetation with the same rainfall regime. Including this relation all varieties of hot and cold deserts or semi-arid climates are possible.[1]

The distinction between arid and semi-arid conditions must be made, on the other hand, to depend on the absence or presence of

[1] Kirk Bryan, The Formation of Pediments, *Rep. XVI Internat. Geol. Congr.*, 11 pp., 1935; compare E. Kaiser, Was ist eine Wüste? *Mitt. Geogr. Ges. in München*, 16 (3), 1923.

base-level control through the agency of rivers flowing to the ocean. In semi-arid regions local base-levels are related to the general base-level, as they are controlled by permanent out-flowing rivers. Owing to low rainfall and high evaporation, however, the out-flowing drainage is of small volume, and the graded gradients of the streams are much steeper than would be those of the larger rivers which would follow similar courses under humid conditions of climate. Nevertheless the presence of these rivers introduces features akin to those of humid landscapes, as the rivers are capable of both vertical and lateral corrasion controlled by stable (or perhaps sinking) local base-levels.

SEMI-ARID MOUNTAIN SCULPTURE

Scantiness of vegetation results, on the other hand, in the development of hill and mountain landscapes rather similar to those characteristic of regions that are completely arid. The discontinuous covering of scrub or tussock grasses, though it forms and binds soil to some extent, does so much less efficiently than continuous forest in humid lands. Under such vegetation the conditions of equilibrium on slopes are very different from those under primitive forest. Slopes do not become graded and stable until they have been reduced to gentle declivities. At all earlier stages they remain rough and rugged, with frequent outcrops of bare rock projecting through a thin soil cover as is well illustrated throughout the schist mountains of the Central Otago district of New Zealand (Pl. VI, 1), as well as on both granitic and non-granitic mountains in Arizona (Pl. IV, 2 and Pl. VII, 2). Structural terraces remain sharp-edged and strongly marked, as in those bordering the Grand Canyon of the Colorado, instead of becoming rounded off and tending to fade out of the landscape as grading of slopes proceeds in a humid climate and more especially under forest (Pl. V, 1). Homoclinal ridges and major geological boundaries are strongly emphasised, as is well shown by air photographs of parts of Australia.

In landscapes composed of similar rocks the texture of dissection is commonly finer under somewhat arid than it is under humid conditions. In Mongolia it is recorded that "in proportion as the mountains become drier the valleys become more closely spaced . . . , for with a thinner web of roots to hold both soil and water

the rain-wash cuts shallow closely-spaced gullies instead of fewer and larger valleys."[2]

Absence of completely protective vegetation leads also to extensive development of badland landscapes, especially on sandy-clay terrains, where much of the rainfall during heavy showers runs off and gullies the bare surface (Pl. V. 2).

Fans and Bahadas

During early stages of a geomorphic cycle under semi-arid conditions accumulation forms may develop abundantly. Much waste is available as the ubiquitous rock outcrops crumble under the attack of physical weathering and as upland areas are dissected, but the streams, being small and intermittent, are capable of transporting this material only down steep declivities. Abundant fans with rather steep slopes are built, therefore, in all depressions of an initial surface, and under appropriate initial landscape conditions these later coalesce to form extensive bahadas and basin plains, and landscape depressions occupied by through-going rivers are deeply gravel-filled to form broad aggraded flood plains. Portions of such accumulations survive, for example, in extensive and very high gravel terraces in the broad valleys of the Clutha system in the semi-arid Central Otago district of New Zealand. Alluvium thus accumulating may overtop divides and isolate portions of the mountain masses, and basin plains and aggraded valley plains may be joined together by the spilling-over of gravel-loaded rivers, while at the same time aggradation is extending farther up valleys, so that perhaps half the landscape may become a continuous plain of aggradation.

Fans and aggraded plains will cease to grow, however, when the supply of waste falls off as a result of lowering of relief in the mountains and reduction of the area subject to degradation. As the supply of waste continues to dwindle and the cycle proceeds farther the aggraded surfaces will in their turn be worn down and dissected by processes among which vertical and lateral stream corrasion will be dominant.[3] Surges, or alternating phases, of vertical and

[2] C. P. Berkey and F. K. Morris, *Geology of Mongolia,* Am. Mus. Nat. Hist., New York, 1927.

[3] C. A. Cotton, *Landscape,* second edition, p. 184.

lateral cutting, may result in the temporary survival of flights of gravel terraces. At an early stage of this reduction the landscape will resemble that of the extensive Mackenzie Plain, the basin-plain of the Upper Waitaki valley, New Zealand, in a district of steppe climate bordering on semi-aridity, where considerable remnants of the maximum fans form terraces above more gently-sloping valley-plains of lateral planation cut in the alluvium.

Planation

Wide plains of lateral planation, the origin of which has been deduced by Johnson,[4] may perhaps at a later stage not only be developed across deposits of an earlier aggradation, but also encroach on and cut away bedrock in low intervalley spurs and ridges, as has already taken place in parts of Central Otago,[5] and possibly also over an extensive zone of the foothills that fringe mountains at an earlier stage of their degradation.

When, eventually, the mountains also waste away to small or moderate relief the whole region will become a peneplain of semi-arid erosion broadly domed and dimpled over the sites of initial tectonic blocks and basins, and still high in parts remote from the sea and from large through-flowing rivers. It has been suggested by Johnson that the Rocky Mountains peneplain in Colorado is a surface of this kind, now dissected. The suggestion is that when cut it was far from plane and that it has been little deformed since by earth movements and perhaps not very much uplifted.[6]

Some parts of a peneplain of semi-arid erosion may be thousands of feet above sea-level, but it will still be subject to lowering of the surface by general down-wearing in early old-age as the supply of debris to be carried off from it diminishes and as stream gradients, already much gentler than those of maturity, become gentler still.

Such portions of a region as are transitional from semi-aridity to aridity must be characterised by conditions intermediate between, or combining features of, semi-arid processes, which differ in only

[4] Douglas Johnson, Planes of Lateral Corrasion, *Science,* 73, pp. 174-7, 1931; Rock Fans of Arid Regions, *Amer. Journ. Sci.,* 23, pp. 389-416, 1932; Rock Planes of Arid Regions, *Geogr. Rev.,* 22, pp. 656-665, 1932.

[5] C. A. Cotton, Lateral Planation in New Zealand, *N.Z. Journ. Sci. & Tech.,* 20, pp. 227*b*-232*b*, 1939.

[6] *Loc. cit.* (4) (*Am. Jour. Sci.*), p. 410.

a minor degree from those operating in humid regions, and those processes which are peculiar to degradation under climatic conditions of extreme aridity (Chapter II).

As has been briefly described in general terms by Bryan,[7] extensive development of semi-arid peneplanation has occurred in the American south-west under climates ranging from "near-desert conditions to semi-aridity." Widely developed and variously sloping smooth surfaces of penultimate degradation in this region, termed "pediments" by Bryan, may be in part plains of lateral planation such as have been referred to above. The rôle of stream corrasion in the development of "pediments" has not been defined to the satisfaction of all disputants, but it would seem from the evidence now available that other processes more closely related to the conditions in streamless landscapes of extreme aridity have operated also to an important extent in developing flat rock-floors in areas remote from permanent streams (Chapter V).

In the North American semi-arid region, Bryan points out, an area of regional extent has been unaffected by the strong Pleistocene to Recent block-fault deformation that has broken up Nevada and south-eastern California, and in the undisturbed region semi-arid peneplanation has been far advanced prior to interruption of rather late date due to depressions of base-level that have led to the initiation of new minor cycles of rejuvenation. The region was in the more distant past (in the Tertiary era) broken up, perhaps more than once, by block-faulting deformation and smoothed again by aggradation before the initiation of the post-Tertiary major cycle of semi-arid degradation by block faulting at the beginning of Quaternary time. "We are dealing," as Bryan puts it, "in this region with a second or third generation of fault-blocks and associated basins." Thus the post-Tertiary peneplain of semi-arid erosion is developed across a "bedrock" that consists in part of Tertiary alluvial deposits in ancient basins and in part of the undermass on which that filling rests as covering strata.[8] In a large part of the region, in which local base-levels are controlled by general base-level owing to the presence of through-going and out-flowing

[7] *Loc. cit.* [(1)].

[8] This is exactly the case in Mongolia also, as interpreted by Berkey and Morris (*loc. cit.* [(2)]).

rivers of the "Colorado, Gila, Altar, and Rio Grande" systems "the drained basins are characterised by erosion surfaces . . . . which extend from the axis of the basin towards each bounding mountain block." Gradients on these surfaces, which are cut partly on "the hard rocks of the mountains" and partly on "the soft rocks of the Tertiary valley-fill," vary in steepness from 10 feet per mile to 250 feet per mile.[9]

Owing to the adjustment to structure that has taken place main streams in this American region of semi-arid peneplanation are now situated in subsequent locations on the soft-rock terrains of Tertiary "valley-fill," and the hard-rock areas of undermass stand out in moderate relief. These have become "in the late stages of the erosion cycle . . . . extensive subconical or tent-shaped ridges" with slopes of from 35 feet to 250 feet per mile, but their smooth surfaces are to some extent "interrupted by sharp-sided residuals." The smooth slopes of the semi-arid peneplain are termed by Bryan "coalescing pediments." He says of them:

> The extensive coalescing pediments that were formed in early Pleistocene time may or may not constitute a true peneplain, but all will admit that they formed a true old-age surface. Late lowering of the main rivers, whether due to regional uplift or to other causes, has brought about general incision of streams and a destruction of much of this surface.
>
> Later less perfect surfaces [he adds] have been formed at lower altitudes. The history of these events is complex and as yet imperfectly deciphered. It is obvious, however, that at each period of stabilised grade on the main river-systems, pediments have been formed by the tributaries, and that the similarities in form between these minor surfaces and the older, more nearly complete surface are very marked.[10]

Incipient Pediments

A typical area has been mapped and described in detail, in the upper valley of the Rio Puerco, a tributary of the Rio Grande, in New Mexico,[11] in which there is found a series of incomplete or incipient pediments, occurring as terrace-like remnants of pene-

[9] Kirk Bryan, *loc. cit.* (1), p. 6.
[10] Kirk Bryan, *loc. cit.* (1), p. 7.
[11] K. Bryan and F. McCann, Successive Pediments and Terraces of the Upper Rio Puerco in New Mexico, *Jour. Geol.*, 44, pp. 145-72, 1936.

plains of semi-arid erosion developed at successively lower levels (Fig. 7). "With respect to the adjacent Basin and Range Province this area is a bordering highland, and its history is similar to that of one of the mountain blocks" within that province. "Post-Eocene," however, is the latest date at which it has been affected by differential upheaval.

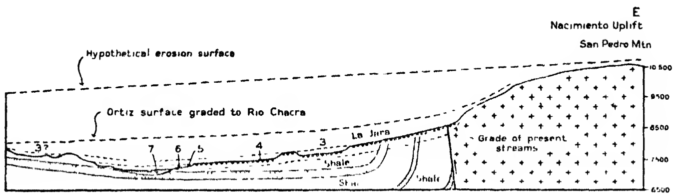

Fig. 7. Ideal profile of successively developed (numbered) erosion surfaces in the upper Rio Puerco valley, New Mexico. (After Bryan and McCann.)

Coalescing Pediments

As regards the two highest erosion surfaces shown in Fig. 7, "some indications of a hypothetical early and widespread erosion surface exist," but "there are more definite traces of a later high-level surface of coalescing pediments," the "Ortiz" surface, which is tentatively correlated with the regional semi-arid peneplain. A considerable remnant of this surface has escaped destruction so as to form the smooth gently-inclined summit of the interfluve (Llano de Albuquerque) between the valleys of the Rio Puerco and Rio Grande (Fig. 8). Other parts of it, at higher levels, are preserved

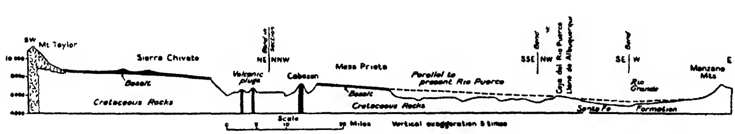

Fig. 8. Profile of the ancient pediment termed the Ortiz surface, preserved in part beneath lava flows and surviving also in the Llano de Albuquerque, New Mexico. (After Bryan and McCann.)

beneath extensive flows of basalt, one part of this "louderbacked" surface forming the Mesa Prieta (Fig. 8).[12]

[12] K. Bryan and F. McCann, The Ceja del Rio Puerco, *Jour. Geol.,* 46, pp. 1-16, 1938.

Below the Ortiz surface are the terrace-like berms of later incipient pediments, which must be regarded as intermediate in character between rock floors of arid erosion (Chapters IV-V) and coalescing valley-floor side-strips of late maturity in humid regions such as have been described by Davis.[13] Where they are dissected the fact is clearly revealed that they are widely cut rock floors only thinly veneered with gravel, as is to be expected on the hypothesis of their development during episodes of stability of local base-levels.

In this district of branching streams lateral planation may have been the dominant process in cutting the erosion surfaces of the low-level incomplete pediments.[14] They are not, however, valley-floors of lateral planation developed along the main stream in the valley, but slope down towards this with the gradient of the smaller side streams that descend from the adjacent unconsumed hard-rock range, upon which the incipient pediments have not encroached very far.

The account of the Mongolian landscape given by Berkey and Morris[15] reveals a striking parallel with the North American western interior. There is a western division consisting of young fault-block ranges and basins, the "Altai type" where deformation of the surface has taken place so recently that pedimentation is not generally far advanced. This division includes the Turfan Basin, the lowest part of the floor of which is 720 feet below sea-level.

In a vast region including the eastern and southern parts of the Mongolian basin, on the other hand, there has been no modern deformation with the exception of some gentle warping, though thick terrestrial formations accumulated here in more strongly warped basins in earlier ages. These, however, are truncated, along with the undermass, by the "Gobi erosion plane" (p. 17), an undulating surface, which corresponds in a general way with the American peneplain of post-Tertiary semi-arid erosion but has been developed perhaps under more truly arid conditions and without base-level control exerted by exterior drainage, though it is suspected that the Pleistocene climate was more humid than that now prevailing.

[13] W. M. Davis, Rock Floors in Arid and in Humid Climates, *Journ. Geol.*, 38, pp. 1-27, 136-158, 1930.

[14] "The principal agent in the formation of pediments is the ephemeral stream, which works by incision and lateral planation" (K. Bryan, *loc. cit.*, p. 1).

[15] *Loc. cit.* (2).

Some localisation of the few unconsumed residual mountains which stand above the Gobi surface on the more ancient rocks results from an adjustment to structure of the same kind as that described by Bryan in North America. Unlike its American analogue the Gobi surface is undissected except by the excavation of desert hollows as described in Chapter II.

The cut surfaces of arid and semi-arid peneplains do not in all cases exhibit the convexity, or grouped convexities, of coalescing rock fans,[16] but in semi-arid regions, in which streams, though most of them are intermittent, flow fairly frequently, they may perhaps be considered to bear the same relationship to rock fans as bahadas do to alluvial fans. For such surfaces fringing mountain bases the term "pediment," as applied and defined by Bryan,[17] seems entirely suitable. (Bryan set out to call the features "mountain pediments," but later shortened this to "pediments.") As he defines the term:

> 'Mountain pediment' has been chosen as the name for such a plain of combined erosion and transportation at the foot of a desert mountain range. The plain ordinarily surrounds and slopes up to the foot of the mountains, so that at a distance the mountains seem to be merely ragged projections above a broad triangular mass—the pediment or gable of a low-pitched roof.

"Coalescing pediments" may eventually replace the mountains and become the chief elements of form of a resulting peneplain, meeting, according to Bryan, in "extensive sub-conical or tent-shaped ridges." To call such features pediments is to extend the original definition, which, however, seems justifiable. Davis has contended that "pediment" should be used only for "young, relatively narrow, uncompleted rock floors," as the word, he says, implies a "subordinate position."[18] Perhaps he mentally confused "pediment" with "piedmont," or, as Bryan himself appears to have done at one stage (1922, p. 88), with "pedestal," when he defined

[16] Kirk Bryan, *loc. cit.* (1), p. 7.

[17] Kirk Bryan, Erosion and Sedimentation in the Papago Country, Arizona, *U.S. Geol. Surv. Bull.*, 730B, 1922; The Papago Country, Arizona, *U.S. Geol. Surv., Water-supply Paper*, 499, p. 93, 1925.

[18] W. M. Davis, Granitic Domes of the Mohave Desert, California, *Trans. San Diego Soc. Nat. Hist.*, 7, p. 233, 1933.

the landform as "a pediment upon which the mountain stands." At any rate Davis's argument has less weight than one he might have based on the domed or arched form, rather than conical or tent-shaped, which he has found that coalescing rock floors assume on the granitic outcrops of the Mohave Desert.

Possibly a distinction will eventually be made between pediments of semi-arid and of arid erosion, but in the present state of lack of knowledge of the quantitative evaluation of the agencies regarded as responsible for "pedimentation," it is impossible to draw a line between them on this basis. Morphologically also they may prove to be indistinguishable, at least with certainty.

Escarpment-fringing Pediments

Progressively dissected pediment strips along the bases of great structural escarpments in semi-arid regions develop some peculiarly characteristic landforms. There are many such piedmont slopes in western North America, where the retreat of escarpments, continually in progress, goes on in association with progressive dissection of early-formed pediments as newer pediments are developed in relation to new escarpment bases.

Progressive pedimentation tends in some cases to obliterate an escarpment (Fig. 9), but earlier-formed piedmont slopes are event-

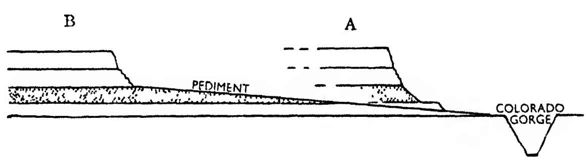

Fig. 9. Two stages (A, B) in the progressive replacement of an escarpment by a pediment. (After Strahler.)

ually regraded, and where the regrading process is accompanied by dissection of an early-formed pediment this results in the production of some special forms. Outlying remnants assume shapes which may be governed not by the terrain and its structure but by processes related to the retreat of the escarpment forming the mountain front. Such features have been mapped and figured

by Rich[19] and by Bradley.[20] The latter has observed that what were formerly rock fans on the steeper part of a pediment fringing the base of an escarpment (Pl. VI, 2) have become isolated by circum-denudation and have in some cases assumed a conical form.

An escarpment in soft rocks may be graded back (Figs. 9, 10) until almost or even entirely replaced by a pediment slope; but, owing perhaps to fluctuation of climate, this pediment may be

A B

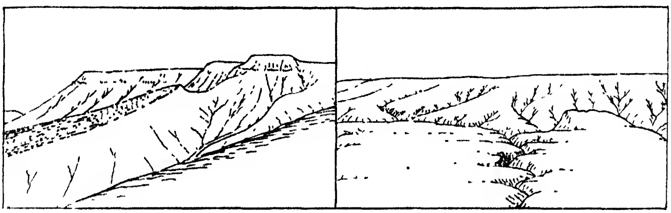

Fig. 10. A, oblique, and B, full-face, views of a submaturely dissected pediment with a "reverse scarp" facing the escarpment of an upland, Shara Murun, Mongolia. (After Berkey and Morris.)

redissected, and gullies then gnaw back into the upland so as to develop a new escarpment, which in turn may be replaced by a new pediment. Along the escarpments descending to the floors of "P'ang Kiang" hollows in the Mongolian desert remnants of successive pediments thus replacing one another have been observed to assume a "reverse-scarp" form, which is illustrated in Fig. 10.[21]

[19] J. L. Rich, Origin and Evolution of Rock Fans and Pediments, *Bull. Geol. Soc. Am.*, 46, pp. 999-1024, 1935.

[20] W. H. Bradley, Geomorphology of the North Flank of the Uinta Range, *U.S. Geol. Surv. Prof. Paper*, 185, pp. 163-99, 1936; Pediments and Pedestals in Miniature, *Jour. Geomorph.*, 3, pp. 244-55, 1940.

[21] C. P. Berkey and F. K. Morris, *Geology of Mongolia*, 1927.

CHAPTER IV

Piedmont Slopes and Lateral Planation

IN the twentieth century much attention has been directed towards the mature, or middle-age, stages of semi-arid to arid landscape development in mountainous deserts, which are well exemplified in the south-western United States and northern Mexico and in the similar but less thoroughly known desert mountains and basins of central Asia.

SKY-LINE PROFILES

In such deserts, where landscapes of strong initial relief are undergoing degradation, the sky-line profiles include a great proportion of long smooth slopes of moderate inclination leading

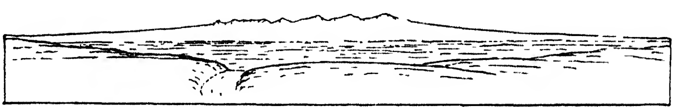

Fig. 11. Landscape profile of the Los Ola Range, in the Mongolian desert. (After Berkey and Morris.)

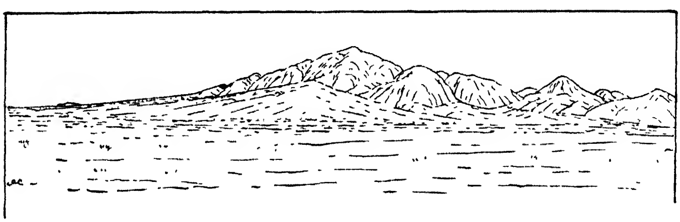

Fig. 12. Pediment fringing Red Mountain, California. (Drawn from a photograph by Professor E. Blackwelder.)

down from the bases of contrastingly rugged mountains towards level basin-floors of relatively small area (Figs. 11, 12). These are the "graded piedmont slopes" described by Davis as characteristic of maturity of the arid cycle (Chapter II). They suggest a predominance of fan-like and bahada forms in the landscape; but the suggestion that the eye receives of a thick alluvial accumulation

underlying the whole of such features is deceptive, and investigation has revealed that "the higher parts of the piedmont slopes may be rock floors, thinly and irregularly veneered with waste" (DAVIS). These forms are now commonly referred to as "pediments" since Bryan's introduction of this term (p. 34), and are regarded as the most characteristic features of broad degradation under semi-arid to arid conditions, but the fact must not be lost sight of that pediment and bahada are forms so closely related that it is impossible to say in the majority of cases where one ends and the other begins. Davis has preferred to use "rock floors" for both bare cut-rock surfaces and those lightly to deeply buried beneath fan or bahada alluvial deposits,[1] but it is unlikely that his lead will be followed in the rejection or even in the restrictive use of "pediment" he has elsewhere suggested (p. 34). In districts where through-going or out-flowing rivers are present (p. 52) bare or thinly-covered ("concealed") pediments or rock floors may slope down to the valley-floors of these rivers, and do not necessarily plunge beneath bahadas of deep alluvium.

PEDIMENTS

As distinguished from forms such as are built of alluvial filling in the deeper parts of undrained basins in early stages of the arid cycle the bedrock[2] features of typical desert and semi-arid landscapes include therefore not only dissected uplands or mountains but also pediments, which are in some cases very extensive, and which may be, according to Bryan's definition (p. 34), either bare (and possibly dissected) or "concealed" beneath a veneer of gravel or finer waste of varying thickness up to about 20 feet. The pediment "ordinarily surrounds and slopes up to the foot of the mountains" (BRYAN), and "the residual mountains that rise from the centre of a well-developed pediment seem to have a high-perched base that is reached by a long and smooth rock-floor ascent" (DAVIS).

> The pediment grows wider as the cycle of erosion progresses, until it may absorb most of the landscape. Hills and mountains

[1] W. M. Davis, Sheetfloods and Streamfloods, *Bull. Geol. Soc. Am.*, 49, p. 1363 (footnote), 1938.

[2] "Bedrock," it must be understood, here includes very weak as well as resistant materials—soft cover as well as undermass of compound structures—where these have formed part of the terrain subjected to erosion in the current cycle.

> are razed and even the bahadas that may have been made early in the cycle are planed off. . . . The pediment, and not the bahada, is the normal and inevitable form developed in the arid regions under stable conditions (BLACKWELDER).
>
> The normal mountain pediment has a smoothly sloping surface more or less covered by alluvium and broken only by scattered hills which rise abruptly from its surface and in many of which are prolongations of the . . . . ridges of the mountains (BRYAN).
>
> When the well-developed Sierrita pediment is seen from a distance, its profile slants outward from the surviving mountain core with astonishing smoothness at an angle of 4° or 3°;[3] indeed, it seems truly rectilinear as it passes from degraded rock to aggraded alluvium until, several miles forward, the declivity gradually decreases to the nearly level floor of an intermont trough. The delicate precision of the distant profile gives it a beauty that one would hardly expect in a line of such simplicity (DAVIS).

Recognition of closely similar forms in the mountainous parts of the Mongolian desert is indicated by the following quotation from Berkey and Morris:

> The gently sloping surface that descends from the mountains is an erosion plane diversified by alluvial fans draped along the front of the range. The slope is concave, steepening towards the mountain base until it attains a gradient of five to seven and even ten degrees, the maximum inclination of the alluvial fans.

These pediment slopes are described as merging at the foot "into the smooth erosion surface which bevels the broad Gobi basin."[4]

The introduction of a name for pediments has resulted in their rapid recognition as important landscape features, though it is quite possible it has led in some cases to unintentional exaggeration of their areal extent at the expense of bahadas, just as the earlier failure of many observers to recognise the presence of bare or only thinly veneered rock floors had led to exaggeration of the relative

[3] According to E. Blackwelder (Desert Plains, *Jour. Geol.*, 39, p. 137, 1031) "the declivities of pediments in the south-western deserts of the United States range from ½° to 7°, with the average of about 2½°. Few exceed 3½°."

[4] C. P. Berkey and F. K. Morris, *Geology of Mongolia*, pp. 330, 332, 1927.

importance of thickly aggraded bahadas. McGee, however, before the end of the nineteenth century fully recognised the fact that vast areas of the "valley plains," as he termed them, of the Sonora desert of northern Mexico are floored by superficial deposits which, though they "have the customary air of great depth," yet "are but a yard or two in thickness for several miles from the mountains, and rest on an eroded surface."[5] Thick alluvium was present, he estimated, under about half only of the area of these great plains.

Lateral Planation

It appears that several processes co-operate in the development of pediments at the expense of desert mountains which are in process of destruction. Parts, though perhaps only small parts of some true desert pediments, and probably considerably greater parts of pediments of semi-arid erosion, may be plains of lateral stream corrasion. These are especially areas in the vicinity of the debouchures of streams of considerable size out-flowing from valleys they have cut in ranges not yet greatly reduced by erosion—that is, in a rather young stage of the cycle, and somewhat early, therefore, in the history of the pediment. At this stage, except under conditions of extreme aridity, such streams, though intermittent, may flow for considerable periods, during which they are fully loaded or overloaded with waste and flow in braided, ever-shifting channels, swinging widely and impinging frequently on the rock walls of mountain-front embayments through which they flow. These embayments have been formed in the fronts of mountains facing desert basins in the early aggradational phase of the arid cycle (Chapter II), and similar valley-aggradation may be expected in the stage of youth of the semi-arid cycle in any region of tectonic initial relief (Chapter III). Lateral corrasion developing widely as lateral planation may cut away spurs of the mountain front and establish a continuous rock floor in their place. The streams at their widest swinging must occasionally undercut and cut back the mountain front on either side of each debouchure; and the strongest advocates of the theory of pediment development by lateral planation are convinced that such strip-by-strip retreat of mountain fronts is the correct explanation of the "back-wearing,"

[5] W. J. McGee, Sheetflood Erosion, *Bull. Geol. Soc. Am.*, 8, p. 102, 1897.

as Davis has termed it, that has so obviously taken place in mature desert mountains, the cut-rock floor of gradually increasing width along the base of the mountain front remaining as a pediment where not too deeply buried by progressive aggradation. This process of lateral planation by streams emerging from the unconsumed residuals of the original mountain blocks is favoured by Blackwelder[6] and by Johnson[7] as the sole or chief agency responsible for the back-wearing of mountains and their gradual replacement by pediments. The latter has pointed out the fan form assumed by some surfaces believed to have been cut by laterally swinging streams that were neither degrading nor aggrading. He has described some steep rock fans so developed at the debouchures of mountain-front ravines, and similar forms fringe the rear margins of some pediments. Remarkably perfect examples occur at the bases of retreating structural escarpments in Wyoming and bear a deceptive resemblance to gravelly alluvial cones (Pl. VI, 2).[8] Johnson regards the whole pediment as made up of such features side by side, though being of larger dimensions the majority of them will have gentler declivities. It may be, however, that pediments of this form and origin exist only in semi-arid districts, such as the San Gabriel Mountains of Southern California,[9] and that a like explanation of very similar forms in more arid deserts must be rejected because of the absence of well defined streams from such deserts.

Johnson assumes in his analysis of the pediment problem that intermittent streams in braided courses will progressively lower the convex areas of pediment over which they are spread out, and that they will do so not in alternating phases of vertical and lateral corrasion but progressively as an accompaniment of lateral corrasion at the margins of their myriad shifting braided distributaries. Such lowering will follow as the natural result of diminution of load in streams as the mountainous areas from which they flow are pro-

[6] *Loc. cit.* (3).

[7] Douglas Johnson, Planes of Lateral Corrasion, *Science*, 73, pp. 174-77, 1931; Rock Fans of Arid Regions, *Am. Jour. Sci.*, 23, pp. 389-416, 1932; Rock Planes of Arid Regions, *Geog. Rev.*, 22, pp. 656-65, 1932.

[8] W. H. Bradley, Geomorphology of the North Flank of the Uinta Mountains, *U.S. Geol. Surv. Prof. Paper*, 185, pp. 163-99, 1936; Pediments and Pedestals in Miniature, *Jour. Geomorph.*, 3, pp. 244-55, 1940.

[9] W. M. Davis, Sheetfloods and Streamfloods, *Bull. Geol. Soc. Am.*, 49, p. 1386, 1938.

gressively worn down by erosion in the course of a cycle, and Johnson argues cogently that lowering of the surface by corrasion must be an essential part of most pediment development, allowing steep rock-fan slopes such as frequently form the rear margins of pediments to be replaced by gentler slopes as the pediments are extended back at the expense of the mountains they progressively replace.[10] This process has been recognised in Mongolia, where "the whole piedmont slope becomes lowered very gradually as the graded streams cut downward, and becomes lengthened very slowly as the mountain front is cut away."[11]

Composite Hypothesis of Pedimentation

Some investigators of the mechanism of semi-arid and arid planation, notably Davis,[12] Bryan,[13] and Rich,[14] have regarded lateral corrasion by streams as only one of several processes operating in parallel in the production of rock floors in deserts. Its part or proportion of the whole effect apparently varies very widely—perhaps from 100 per cent to zero—and seems to approach the latter in parts of the arid Mohave desert investigated by Davis. Its part seems to diminish with increasing aridity and with dwindling relief and area of undissected upland or mountains—that is, as intermittent streams and streamfloods become rarer features of the landscape. In the Mohave desert Davis's search for the bluffs that would give evidence of lateral cutting by streams at the bases of mountain-front slopes, and especially along the sides of the ubiquitous embayments of the mountain-fronts, failed to reveal traces of the occurrence of any such general process operating efficiently at present as a cause of the extension of the pediment at the expense of the mountains

[10] *Loc. cit.* (7) (*Geog. Rev.*), pp. 662-3.

[11] C. P. Berkey and F. K. Morris, *loc. cit.* (4), p. 331.

[12] W. M. Davis, Rock Floors in Arid and in Humid Climates, *Jour. Geol.*, 38, pp. 1-27, 136-58, 1930; Granitic Domes of the Mohave Desert, *Trans. San Diego Soc. Nat. Hist.*, 7, pp. 211-58, 1933; Geomorphology of Mountainous Deserts, *Rep. XVI Internat. Geol. Cong.*, 12 pp. 1936; Sheetfloods and Streamfloods, *Bull. Geol. Soc. Am.*, 49, pp. 1337-1416, 1938.

[13] Kirk Bryan, Erosion and Sedimentation in the Papago Country, Arizona, *U.S. Geol. Surv. Bull.*, 730B, 1922; The Papago Country, Arizona, *U.S. Geol. Surv., Water-supply Paper*, 499, 1925; The Formation of Pediments, *Rep. XVI Internat. Geol. Cong.*, 11 pp. 1935; Processes of Formation of Pediments at Granite Gap, *Zeitschr. Geomorph.*, 9, pp. 125-35, 1935.

[14] J. L. Rich, Origin and Evolution of Rock Fans and Pediments, *Bull. Geol. Soc. Am.*, 46, pp. 999-1024, 1935.

at its rear. Scattered examples of bluffs obviously due to lateral stream corrasion that were found in relation to the Mohave streamfloods were only sufficiently numerous to indicate the kind of form that might be looked for, and were quantitatively insignificant in the landscape.

Bryan's statement that "the principal agent in the formation of pediments is the ephemeral stream, which works by incision and lateral planation,"[15] refers, without doubt, to the conditions in parts of the North American desert region that are not extremely arid. Even in those parts he finds true fan-form convexity characteristic of portions only of the pediments he has studied in detail. These

> occur opposite individual canyon-mouths. Their inclination and convexity are related to the size and duration of the floods emanating from the canyons and to the load of detritus brought down. The form is . . . dependent for existence on a considerable detrital load. This load is gained within the mountains and implies a considerable drainage area still being vigorously eroded. In part the convexity of contour is brought about by the temporary deposit of the detrital load on the pediment. In part the shifts in channel induced by the temporary deposition of detritus cause more rapid erosion of the rock floor at the margins of the area of development than at the centre. With the progress of the erosion cycle vigorous denudation within the mountains ceases, the detrital load decreases, and the fan form tends to disappear (Bryan).
>
> Lateral planation [he says] can occur only when water of sufficient quantity runs in channels of an effective size, and carries an adequate load of debris for use in abrasion. The duration of flow is also important in that small volumes of water over a long period are more effective than larger volumes over a short period. As pediments are formed in arid regions, most of the streams are strictly ephemeral. They flow for periods of a few minutes or hours during and after rains. There are many localities which have such small drainage areas that no large streams result even from unusually heavy rains. Such places are obviously unfavourable for lateral planation. In such places also the rate of removal of debris may exceed the production by weathering, so that a debris-load adequate to act in abrasion may be absent.

[15] The Formation of Pediments, *loc. cit.* (18), p. 1.

Bryan points out that some considerable parts of pediments—not merely inter-fan re-entrants, but even the areas within some mountain-front embayments, and bordering stream channels—are concave surfaces, that is, "have contours concave downstream," and regards these as analogous, perhaps even homologous, with those parts of valley-floors of humid regions—"side-strips"—developed not by lateral corrasion of the main stream in the valley but by back-wearing of the valley-sides, as deduced by Davis.[16] As compared with humid-valley side-strips arid pediments are relatively steep because "the rock waste to be carried [across them] is great in quantity and coarse in texture" (DAVIS). "They differ from the floors of mature or post-mature valleys of humid regions only in the steepness of grade and in the sharpness of the bounding angle between the floor and the side walls of the valley" (BRYAN), and even this latter distinguishing character is inconspicuous in at least some non-granitic terrains.[17]

Where the local base-level has fluctuated, concavity of pediment surfaces in valleys or embayments of a mountain front may be due in some cases to development of a progressively buried concave rock floor by lateral stream-planation accompanying aggradation, this being followed by removal of the detrital cover from the rock floor.[18] If attention be confined, however, to the uninterrupted cycle of mountain-destruction by pediment-development, or replacement of mountains by pediments, it would appear that convexity of surface in and in front of the debouchures of considerable streams from the mountains must be expected in early stages, whatever process may be dominant in causing the retreat of the mountain front. At this time there is still an abundant and coarse load of rock debris from the mountain valleys to be evacuated, and this requires rather steep gradients for its transportation across the pediment, so that the surfaces over which floods move this waste remain higher than intermediate parts of the pediment, where there is a much smaller quantity of debris, and that of finer texture, to be carried away, allowing the pediment to be developed at, or to be degraded to, a lower level.[19]

[16] *Loc. cit.* (12), 1930.
[17] W. M. Davis, *Loc. cit.* (12) (1938), p. 1359.
[18] C. A. Cotton, Lateral Planation in New Zealand, *N.Z. Jour. Sci. & Tech.*, 20, pp. 227B-232B, 1939; *Landscape*, second edition, p. 179. [19] J. L. Rich, *Loc. cit.* (14).

In the later stages of the cycle, distinct fan forms opposite the points of emergence of the major streams from the mountains would gradually give place to the broad, smooth pediments . . . having more nearly the form of aprons than of fans, and the sharp mountain valleys that characterise the earlier stages would give place to broad sags between the aprons leading up to the wasted remnants of the mountains (RICH) (see Fig. 13).

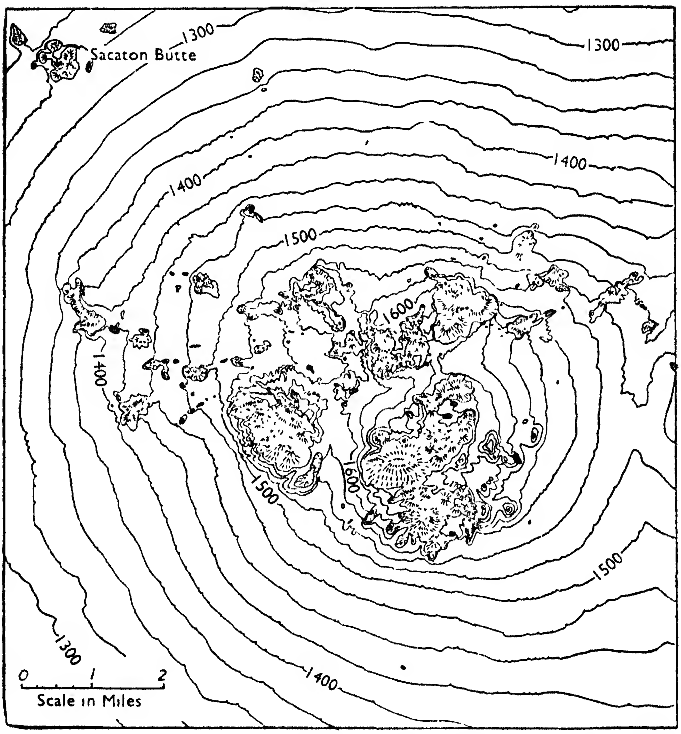

Fig. 13. Late mature pediment surrounding Sacaton Mountains, Arizona. (After Rich.)

Davis has found the floors of embayments in mountain-fronts in the arid Mohave desert generally to exhibit fan-form convexity. It is "repeatedly found that the mountain-face embayments which head in deeply eroded mountain valleys and drain to aggrading playas are fan-shaped and detritus-covered" (DAVIS), though the

cover is generally of no great thickness and the rock floor beneath it is also fan-shaped. Where a local base-level is not rising, a rock floor or pediment "need not be buried under an aggrading cover after the water courses have established a graded flow" (DAVIS). Fan-form convexity of either a buried or bare surface does not, according to the deductions and observations of Davis,[20] establish the hypothesis of lateral planation as the explanation of its origin.

Three processes, according to Bryan, combine to produce pediments, namely, "lateral planation by streams, rill work, and retreat of mountain slopes." He does not, like Johnson, ascribe "retreat of mountain slopes" entirely, or even chiefly, to undercutting by streams in the course of lateral planation, and where this process, owing to a general absence of streams, has its minimum efficiency slope-retreat may be entirely due to another cause, namely progressive weathering leading to what Davis has termed "back-wearing." The back-wearing hypothesis will be discussed in Chapters V and VI.

PIEDMONT SLOPES

The pediment and bahada slopes are so closely related, and so often indistinguishable, that they are best considered, as is done by Davis, as one "piedmont slope." According to this investigator, where streams and streamfloods are absent sheetflood action ("rill work" of Bryan) is the agency that grades piedmont slopes in front of the mountains and residual uplands of arid deserts. It has not been suggested, however, that sheetfloods cut back a mountain-front: back-wearing is a fact that has to be accounted for in another way. The piedmont slope consists, as has been consistently observed, of the bahada as its principal element in young to mature deserts of interior drainage and rising base-level, but the deposits of which the bahada is built thin to a feather edge, so that the bahada gives place near the mountain-base to a bare rock floor or pediment.

The investigator of piedmont slopes looks for examples in which the formative grading processes responsible for the production of the perfect form have not been interrupted with consequent burial or erosion of the surface. In nature the grading process has rarely been quite continuous. It is interrupted, or its continuity is broken, by fluctuations of local base-level due to pulsations of climate, cap-

[20] *Loc. cit.* (12), 1936 and 1938.

tures of drainage, and possibly other causes. The personal equation enters into the interpretation of a surface as on the one hand simple or on the other hand either buried subsequently to its development or stripped of a former alluvial cover and, when bare, roughened by shallow dissection. Deeper dissection leaves less room for difference of opinion.

CHAPTER V

Sheetflood Erosion or Rock-floor Robbing

In an arid desert streamfloods, according to Davis,[1] are of rather local occurrence, being due to somewhat exceptional forms of surface relief, while sheetfloods, though infrequent, are the only form of off-flow possible on large areas of smooth piedmont slopes.

> The condition essential to the formation of a sheetflood appears to be a heavy rain draining [from the mouth of a mountain-front valley] to or falling directly on a barren, graded detrital slope, where, immediately loaded to capacity, the flood may flow freely. A secondary condition appears to be the absence of a low-water stream during the long interval between sheetfloods; for such a stream would develop a channel in the detrital slope, and the channel would delay, if not prevent, the outspreading of the next sheetflood (Davis).

The surfaces on which the traces of sheetflood flow are found are detritus-covered, but the detrital layer may be thin, and the surface may be a pediment according to Bryan's definition. Surfaces of almost bare rock have been observed with a pattern of close-spaced shallow channels of ephemeral rills described by Bryan as marking "the position of the swiftest threads of run-off during rains," though "during great rains the whole surface is covered by moving water." The observed rill-networks have been interpreted by Davis as features of the normal beds of sheetfloods (Fig. 14), and similar rill patterns have been described by Jutson as characteristic of surfaces overspread by sheetfloods in Western Australia.[2] In Mongolia also Berkey and Morris record the presence of "an infinite network of shallow rill courses."[3]

Davis describes the little channels fashioned and left by sheetfloods on "detrital slopes" of bahadas and concealed pediments as "enmeshed" in a pattern that may be said to be "composed of a

[1] W. M. Davis, Sheetfloods and Streamfloods, *Bull. Geol. Soc. Am.*, 49, pp. 1337-1416, 1938.
[2] J. T. Jutson, Sheetflows or Sheetfloods . . . , *Am. Jour. Sci.*, 48, pp. 435-9, 1919.
[3] C. P. Berkey and F. K. Morris, *Geology of Mongolia*, pp. 330, 332, 1927.

multitude of fan-like units commonly measuring from 300 to 500 feet in length . . . , each unit made up of a myriad of interlacing courses" (Fig. 14). He continues:

> The narrow, up-slope part of a unit is a gathering ground where detritus is picked up; here some erosion is accomplished.

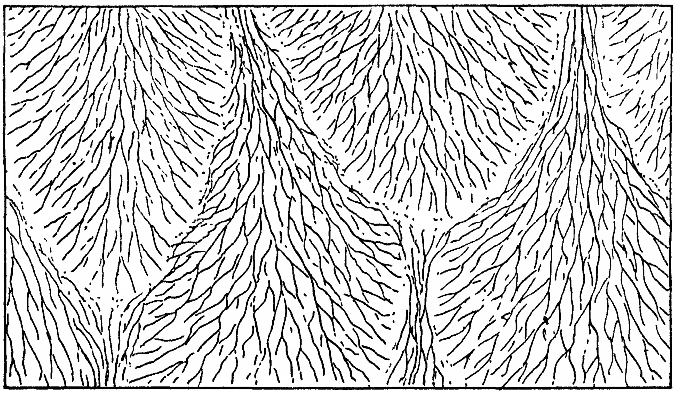

Fig. 14. Davis's "idealised diagram of the enmeshed lines of sheetflood flow."

> The larger, down-slope lobe is a depositing ground; there detritus is laid down in a delta-like sheet with a fairly well defined front. At the climax of a flood the surface of the slope in a flooded area is completely submerged; but, as the flood subsides, its dwindling residual streamlets survive only along the main channels adjoining the head of each fan-shaped unit, and these channels are then more or less interrupted by shoals. As the units are not sharply separated, there must be much spill-over from the depositing lobe of one unit to the head channels of the next, the growing frontal border of each delta advancing somewhat on the upper parts of the units next below. There must also be a certain amount of lateral rearrangement, whereby marginal currents shift their allegiance from one unit to another. Thus the units change their shape and size, and shift their position; their complexities are manifold. The braided flow of gravel-laden rivers and the low-water braided flow of silt-laden rivers in humid regions resemble the enmeshed drainage lines of sheetfloods in arid regions.

Transportation of Debris by Sheetfloods

After quoting a vivid description of infrequently occurring sheetfloods in action from the eye-witness account of McGee, Davis comments:

> One of the most striking peculiarities of sheetfloods is the shortness of their flow in distance as well as in time. That is because they are fed by local and short-lived downpours of rain and because they are eagerly absorbed by the dry and pervious detrital slopes. They gain in depth while the rain lasts, but they soon lose the gain by soaking into the dry ground after the rain ceases; and so, before running more than a few miles, they vanish. The transportation that they accomplish is therefore patchy in area as well as spasmodic in duration. Only occasionally are longer paths of flow or "washes" seen, perhaps the work of exceptional floods. The lateral limits of a flood are also ill-defined. Where there are mountain spurs or a few mounts, knobs, and hillocks, which represent the former extension of the spurs, these serve to separate the floods that come from neighbouring mountain valleys; but adjacent floods may become confluent after the divides are passed.

The extreme infrequency of the sheetfloods that transport waste down piedmont slopes, their local nature (due to concentration of heavy cloudburst rainfall in small areas), and the shortness of the times during which they flow are all characteristic. Some of the cloudbursts cause torrential floods which are gathered into streams in the ravines of the mountains. After issuing from a valley-mouth such a flood

> quickly spreads into a sheetflood, which, running slower and at the same time picking up whatever additional detritus it can carry, promptly becomes fully loaded. Thereafter, the stream losing volume by in-soaking, the load is gradually laid down. . . . On the other hand, if the heavy rain falls directly upon the detrital slope, the sheetflood is formed at once. Then its thicker and faster-flowing part, quickly loaded to capacity, overtakes the thinner down-slope part, and, while thus gaining depth and velocity, it increases its load. But as soon as its depth and velocity are lessened by in-soaking, deposition begins and continues until the flood vanishes.

While recognising the possibility of some "sheetflood erosion," as McGee has termed it, Davis has credited sheetfloods mainly with the work of transportation and deposition of the debris derived from wasting mountain-fronts, carrying it across nearly bare pediments and thence down bahada slopes to deposit it in part on the bahadas and in part on playa floors. This is summarised by Davis as follows:

> When the streamfloods emerge from the canyons or valleys at the mountain front, they spread out into sheetfloods, which deposit the load [derived from erosion in the mountains], pick it up again, and carry it along in steps, regulating and building up the surface of the bahada, and eventually delivering the finer material to the aggrading playa.

Bahadas built in such fashion do not assume quite the same form of coalescing strongly-convex fans as do those built by aggrading streams of semi-permanent flow, but their slopes are smoother and more uniform. As stated by Sauer in a description of the Chiricahua Mountains, in Arizona, "conspicuous fan surfaces are strikingly wanting. The contours along the west flank . . . . are pretty emphatically parallel and straight. Bulges opposite the canyon mouths are not notable. . . ."[4]

Davis's descriptions and figures all indicate, however, that wherever drainage from a mountainous hinterland flows out into mountain-front embayments, in front of each of these a fan-form convex segment of the piedmont slope develops, but the interfan angles between these are not generally so pronounced as to cause them to collect and guide streamfloods. The occurrence of streamflood courses in intersequent positions has been noted only where piedmont slopes from different mountain areas meet in the "physiographic axes of intermont depressions or troughs" or "slant obliquely towards each other and meet along in-turned contour lines," and where sheetfloods are guided by the piedmont slopes so that they "run against an interfering spur or mount" (Davis).

Davis's observations in the Mohave desert show that broad bare-rock pediments do not form proportionally large parts of piedmont slopes as these are normally developed bordering mountains that

[4] C. Sauer, Basin and Range Forms in the Chiricahua Area, *Univ. Cal. Publ. in Geog.*, 3, p. 383, 1930.

still retain considerable relief; but he has found that extensive bare-rock "floors" are present in the more advanced cycle-stage at which mountainous areas have been reduced to low "domes." Some bare-rock zones with a width of several miles, where such are found surrounding or bordering mountains of considerable relief, are explained by him—in the case where degradation of the mountains and development of the normal piedmont slope have taken place with respect to a rising base-level—as the result of stripping of formerly buried floors owing to a change of conditions akin to interruption by a new cycle of erosion. He has found such bare pediments not only stripped of cover but also roughened by trenching due to streamflood erosion under the changed conditions, but the work of streamfloods may continue until the rock surface wastes away to smoothness again under the attack of a "down-wearing" degradational process, when a change back to sheetflood drainage may again become possible.

Pediments in Externally-drained Regions

Of greater importance than might appear from the proportion of attention that has been given to the development of piedmont slopes in areas where local base-levels are rising is the case where the local base-level is stable or sinking owing to its being controlled either by out-flowing rivers or the lowering of the general land surface which results from aeolian exportation of dust from an arid basin. Such conditions generally favour the reduction of true bahadas to small dimensions, or rather the development of pediments instead as the predominant element in piedmont slopes superficially like those of bahadas. These may be "concealed" in part by a gravel cover of moderate depth, being revealed only when stripping of the cover takes place as a response to some change in local base-levels, but in all cases the cover will thin out and become discontinuous close to the mountain base at the rear of the piedmont slope.

The necessity for consideration of base-level control by out-flowing rivers introduces the climatic transition to semi-arid, in contrast with arid, conditions, and opens up the unsettled question of how great a part in pedimentation must be ascribed to ordinary river planation.

The Back-wearing Process in Pedimentation

Closely bound up with the problem of pediment development is the question of the processes concerned in bringing about the retreat of mountain fronts as they give place to pediments.

If Johnson's theory of mountain-front retreat due to lateral planation be not accepted as a complete explanation of pediment extension, the gnawing-back of the rear edges of piedmont slopes into desert mountains must be ascribed largely to the third of the three processes credited by Bryan with the work of desert erosion on these slopes, namely, "lateral planation by streams, rill work, and the retreat of mountain slopes." The theory of the last-mentioned process (termed by Davis "back-wearing") has been developed deductively with great thoroughness by Lawson.[5] He reaches the conclusion that the mountain front must retreat without change of slope, or "parallel to itself," though not quite horizontally, as it is attacked by the desert processes of physical weathering and rain-wash, and that as it retreats a rock floor must be developed at its base and grow in width. He does not envisage the actual emergence, in an ordinary case, of the rock floor as a bare pediment, but deduces its formation and simultaneous burial beneath a bahada spread in front of the retreating mountain face.

The base-level condition postulated by Lawson is that prevailing (as assumed in the stage of youth in Davis's ideal arid cycle) where accumulation of waste on the floor of each separate desert basin causes rise of local base-levels. As bahada slopes will remain essentially of the same declivity during this process, the bahada surface must rise approximately parallel to itself; and this explains the progressive burial of the developing rock floor or potential pediment along the mountain front (Figs. 15, 16). Davis has more recently described long piedmont slopes in the Mohave desert which descend generally to playas and are waste-covered throughout, as is required by Lawson's deduction.

An essential part of the deduction is that the buried rock floor (termed "suballuvial bench" by Lawson) will be convex (Figs. 15, 16), whereas, Davis[6] has since maintained, by contrast pediment

[5] A. C. Lawson, Epigene Profiles of the Desert, *Univ. Cal. Publ. Bull. Dep. Geol.*, 9, pp. 23-48, 1915.

[6] *Loc. cit.* (1) (1938), p. 1404. Concavity of pediment slopes has been insisted on also by Sauer (*loc. cit.*).

slopes developed subaerially may be expected to be concave in down-slope profile "because the load of their sheetfloods comes chiefly from the mountains, and as the load is refined in texture the gradient of the rock floors should decrease." The reason for the convexity of a rock floor buried progressively as it is developed is related to the fact that rise of the extending bahada surface will

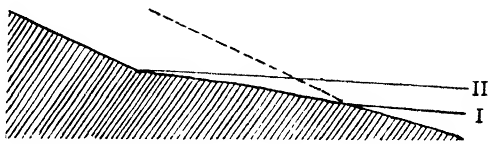

Fig. 15. A retreating mountain-front, at the base of which a rock floor is developed and progressively buried under accumulating alluvial gravel. The broken line and the full line parallel to it at the left are successive positions of the mountain front; I and II are corresponding surfaces of the bahada. (After Lawson.)

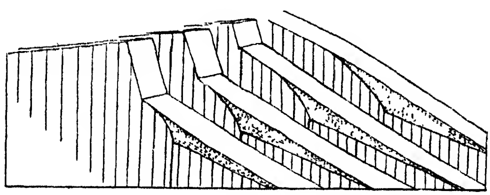

Fig. 16. Diagrams of progressive retreat of a mountain front (initially a fault-scarp) and its eventual destruction by back-wearing. In early stages of the retreat a developing rock floor is progressively buried beneath alluvium. (After Davis.)

become slower as its area increases, and there will not normally be a compensating increase—or any increase at all, more probably diminution—in the supply of waste from the mountains. The first-formed strip of rock floor will be appreciably steeper than the first-deposited layers of bahada alluvium that rest on it, but as the rock floor grows wider (following retreat of the steep mountain front) during the period of progressively slower rise of the bahada (and of local base-level) its slope becomes more and more nearly parallel with the bahada slope (Figs. 15, 16). The alluvial cover will thus thin to a feather edge in the vicinity of the still retreating mountain front.

In the case of normally rising base-level in a desert basin with growing bahadas development of a belt of bare rock-floor or true

pediment is regarded by Lawson as possible, but only as a narrow strip (merging down-slope into a broad bahada) at a late stage of the process of mountain-front retreat. Then perhaps a mile or two miles width of smooth bare-rock pediment may be found, "across which the detritus from the vanishing front is swept in times of cloudburst" (LAWSON). The extension of Lawson's back-wearing hypothesis to explain broader bare or only lightly covered ("concealed") pediments requires the introduction of a postulate of stable or sinking local base-levels. Such conditions may be expected to persist for long periods in arid to semi-arid regions of external drainage after a youthful episode of aggradation has come to an end (Fig. 17). Bahada surfaces, now no longer rising, have become slopes "of transportation of the available debris towards the local base-level," while pediments extend at the expense of wasting mountains.[7] Though lowering of base-level may take place also in a senescent stage of a desert with interior drainage (p. 24), extension of piedmont slopes at the expense of mountains may be no longer possible in such a case, as the mountains will in most cases have been already destroyed.

Notable examples of bare or nearly bare pediments, some of which remain in perfect condition over large areas, have been described in southern Arizona and Sonora by Bryan,[8] and earlier by McGee,[9] and the contrast of these with detritus-buried rock floors in the Mohave Desert has been recognised to be a result of their relation "to the Yaqui, an ocean-reaching, though intermittently flowing, river."[10]

The history of the development of the Sonoran pediments may be supposed to begin in the youthful stage of the current cycle with an episode of deep aggradation (Chapter III) during which the streams outflowing from this arid to semi-arid region graded their necessarily steep profiles. After this maximum-bahada stage had been attained (Fig. 17, FP), and a convex rock floor FR had been buried, degradation of entire piedmont slopes would take place, while at the same time mountain-front retreat from

[7] Kirk Bryan, The Papago Country, Arizona, *U.S. Geol. Surv. Water-supply Paper*, 499, 1925, p. 100.

[8] *Loc. cit.* (7).

[9] W. J. McGee, Sheetflood Erosion, *Bull. Geol. Soc. Am.*, 8, p. 110, 1897.

[10] W. M. Davis, *loc. cit.* (1) (1938), p. 1405.

F to K was in progress in the long enduring stage of maturity; and the present-day condition has eventually been reached, in which the piedmont slopes for about half of their breadth are bare-rock floors (KL), which lead down to degraded bahadas (LV).

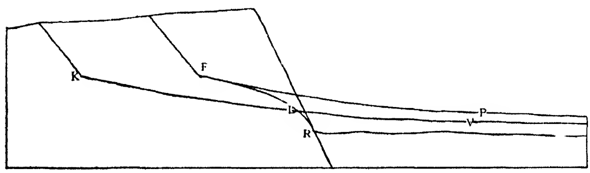

Fig. 17. Ideal section of Sonoran rock floors (pediments). (After Davis.)

The degradation of rock floors and bahadas may perhaps be ascribed to McGee's[11] rather imperfectly defined process of "sheet-flood erosion," or "rock-floor robbing" by sheetfloods, which Davis studied in operation on the worn surfaces of granite domes in the Mohave Desert (Chapter VI). Davis, on the other hand, favoured for the explanation of pediments of the Sonoran type a hypothesis of degradation by alternate gullying and planation. Imagined details of the latter process of progressive degradation include episodes of "transformation of the sheetfloods into streamfloods, the stripping of the cover and the trenching of the underlying rock floor, the eventual consumption of the inter-trench ridges, and the restoration of sheetfloods on a smoothed rock surface."[12]

Under conditions favouring slow degradation, however, sheet-floods are no longer fully loaded, and they therefore strip loose debris from the slopes down which they flow, expose the rock floor, and "rob" it, to use Davis's expression, of the fragmentary products of the gradual decay which follows its exposure. It seems reasonable to extend this theory of sheetflood erosion as expounded by Davis in his explanation of the form of granite domes[13] to the gradual lowering of pediments bordering residuals which have been reduced to moderate relief and which, though they may not yet have reached the penultimate stage of destruction, are no longer

[11] *Loc. cit.* (9).

[12] W. M. Davis, *loc. cit.* (1) (1938), p. 1405.

[13] *Loc. cit.* (1); also Granitic Domes of the Mohave Desert, *Trans. San Diego Soc. Nat. Hist.*, 7, pp. 211-58, 1933.

yielding a large supply of debris.[14] The gap between the theories of sheetflood control of piedmont slopes and Johnson's hypothesis of degradation by lateral planation and control by widespread braided networks of ephemeral streams is thus almost bridged.

Concave Pediment Profile

The theoretical contrast between a concave exposed rock floor, or pediment, developed during degradation of a piedmont slope and a convex floor developed according to Lawson's scheme and progressively buried by bahada deposits as it is cut is shown in Fig. 17. It has been shown, however, by Johnson[15] that convexity of a rock floor progressively buried is not inconsistent with a hypothesis of continuous regrading of exposed strips of pediment to lower levels during mountain-front retreat. If an originally buried rock floor of resistant rock should be stripped of its cover as a result of rapid lowering of base-level and be exposed in a well-preserved condition, pronounced convexity of surface form might be found to survive on it, as described by Davis in the pediment on the western side of the Santa Catalina Mountains, in Arizona.[16]

The "Gobi Erosion Plane" of Mongolia

Rock-floor robbing has been observed in Mongolia, and may be the process chiefly responsible for the development of the enormously extensive desert plain of that region. Bahadas are scanty, and the vast area of rock floor, only thinly veneered in parts with gravel, indicates that denudation either is now or very recently has been in progress with respect to local base-levels that are not rising but are almost certainly being lowered gradually by the process of dust exportation. "The wind does not contribute to the carving of the erosion surface except in a very minor degree; the chief rôle must be ascribed to the myriad short-lived streamlets acting upon the weathered rock of the piedmont."[17]

[14] Bryan has described a similar process operating on an exposed pediment, terming it "rill work" (K. Bryan, Processes of Formation of Pediments at Granite Gap, *Zeits. Geomorph.*, 9, pp. 125-35, 1935).

[15] Douglas Johnson, Rock Planes of Arid Regions, *Geog. Rev.*, 22 pp. 656-65, 1932.

[16] W. M. Davis, The Santa Catalina Mountains, Arizona, *Am. Jour. Sci.*, 22, pp. 289-317, 1931.

[17] Berkey and Morris, *loc. cit.* (3), p. 330.

The "bedrock" is described as "deeply weathered and disintegrated," and its surface is "thinly and unevenly strewn with small chips of native rock" and exhibits "an infinite network of shallow rill courses."

Piedmont slopes thus described merge into the more nearly level "smooth erosion surface" in intermont basins, showing that development of the desert surface has passed beyond the stage characterised by the presence of bahadas, or else that this stage of the desert cycle has locally been elided.

Air photographs of the northern part of the Libyan Desert suggest that that region affords an example of a landscape mature in a cycle which will lead to the development of a senile surface like the "Gobi erosion plane". Already there is an extensive development of wide and branching valley floors which seem closely analogous with pediment embayments in mountainous deserts. These pediment tentacles reach to the heads of innumerable side valleys of dendritic pattern in a maturely dissected landscape, and must eventually coalesce to become a pediment of wide extent thinly veneered with waste which will be frequently stirred and moved about by sheetfloods and by wind.[18]

[18] See *National Geographic Magazine,* 81, p. 513, 1942.

CHAPTER VI

Desert Mountains, their Dissection, Decay, and Destruction

The fronts of desert mountains (and also the slopes of smaller residual hills) characteristically appear to make somewhat sharp angles with the gentler piedmont slopes (Fig. 18), and these re-entering angles are among the most striking features of mature desert profiles, perhaps because of the contrast they introduce with the smoother

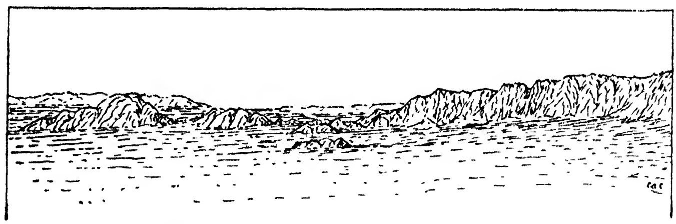

Fig. 18. The re-entering angle between piedmont slope and mountain front, Granite Mountains, Mohave Desert, California. (From a photograph.)

transition in an open concave curve from steep to gentle slopes with which most observers are familiar in humid regions. It should be noted, however, that geomorphologists of the school of W. Penck maintain that the appearance of an angle between range-front and piedmont slope that has been reported by various observers is an illusion, which may be dispelled by close examination of the apparent angle.[1] The illusion, if such it be, may be due in part to the fact that the mountain fronts "appear smooth and wall-like from a distance because the secondary spurs are of similar length and steepness" (Sauer). With this view the following objective impression may be contrasted:

> One receives the impression when travelling over the plateau [of Tibet] that a once mighty range of mountains as

[1] C. Sauer, Basin and Range Forms in the Chiricahua Area, *Univ. Cal. Publ. in Geog.*, 3, pp. 367-8, 1930.

> ages passed had crumbled away and filled up its canyons and valleys until now only the mountain tops showed but a hundred or so feet above the plain.[2]

The mountain-base re-entering angle (Fig. 18), though noticeable whatever rocks the mountains are composed of, is very much sharper and more conspicuous in granitic than in non-granitic rocks. It is clearly related to two chief causes: (1) persistence of the steep profile of youth in all rock slopes on and within the mountain front, and (2) absence or small development of talus slopes of the debris of rock disintegration at the bases of steep slopes, which, if present, obscure the angle. The second condition characterises slopes of granitic rocks weathering in an arid climate, but is found also in the case of some volcanic rocks. In such rocks "the large angular joint blocks . . . . weather into rounded boulders, grains, and dust, without scraps of intermediate size" (DAVIS).

In general "the hard-rock slopes of desert ranges which shed large spalls [because they have widely-spaced joints] are steep, while those which shed small fragments have a low angle; ranges composed of hard rock which are thus naturally steep maintain their steepness as long as the rock slopes endure" (LAWSON).[3] With this may be contrasted Davis's finding that resistant rocks other than the granitic and some volcanic rocks mentioned in the preceding paragraph are broken up by weathering into fragments of assorted sizes instead of crumbling from boulder size into grains and dust, as granites do. These "miscellaneous" rocks and also "more closely jointed materials" are "for the most part covered by detritus of intermediate size, which blends by gracefully concave basal profiles into the graded piedmont slope."[4]

On the mountain slopes and valley sides of southern Arizona Bryan[5] has compared the steepness of slopes developed on various types of rock and thereafter maintained without change of declivity as mountains waste away and are replaced by piedmont slopes. Only soft materials, such as shale and compact tuff, which weather

[2] E. G. Schary, *In Search of the Mahatmas of Tibet*, p. 139, London, n.d.

A. C. Lawson, Epigene Profiles of the Desert, *Univ. Cal. Publ., Bull. Dep. Geol.*, 9, pp. 23-48, 1915.

[4] W. M. Davis, Sheetfloods and Streamfloods, *Bull. Geol. Soc. Am.*, 49, p. 1359, 1938.

[5] Kirk Bryan, The Papago Country, Arizona, *U.S. Geol. Surv. Water-supply Paper*, 499, 1925.

readily into fine waste, develop characteristic slopes of less than 20°. Very steep slopes are developed on somewhat rare outcrops of rocks, chiefly igneous, which become broken into very large joint-bounded blocks that are not easily dislodged; but the most commonly occurring slopes are of intermediate steepness and are developed on bedded lava flows and on granite, the characteristic slope on the latter being from 30° to 35°. The lava outcrops shed fragments two to six feet in diameter, and these, though they are intermittently removed by floods during cloudbursts, accumulate meanwhile, partially filling up and so obscuring the characteristic angle between steep mountain and gentle piedmont slopes. In granite, on the other hand, true "boulder-controlled" slopes are developed, *with little or no talus at the base* (Plate VII, 1). Boulders of mixed sizes from 10 feet in diameter downward, governed in size by the spacing of joints, lie thinly (one deep) on the slope, where they are undergoing rapid disintegration by weathering. Occasionally one rolls down, but as it does so it crumbles. Only fine material, some of which is washed down during every cloudburst, reaches the foot of the slope, and this is carried away normally by sheet-floods down the piedmont slope. Thus is explained the absence of talus accumulations and the permanent exposure of the characteristic sharp re-entering angle between a steep boulder-clad slope and the gentler piedmont slope at its foot.

The boulders of steep granite slopes originate, Davis[6] has pointed out, in sub-surface weathering as residual cores and are exposed at the surface only when fine-grained disintegrated material has been washed away from around them. The usual mode of retreat of a granite slope that is boulder-clad as a result of such denudation he ascribes to back-wearing unassisted in the desert by any undercutting due to corrasion at the base—a process "in which the weather, together with rain and rill wash, attacks the whole height of . . . mountain faces."[7]

Forms Peculiar to Granite Terrains

The prominence that has been given in descriptions of American desert mountains to forms developed on granite terrains tends to

[6] *Loc. cit.* (4), p. 1360.
[7] *Loc. cit.* (4), p. 1383.

create a false impression that such are the characteristic forms of desert erosion, whereas they owe at least as much to the terrain as to the climate. Granite tors and bouldery granite surfaces are not confined to deserts. They are, however, more prominent under arid than humid conditions because of the exposure of the surface to rain wash in the absence of vegetation and the consequent more complete removal of the fine products of weathering. Davis has shown that under humid to semi-arid conditions debris is retained and soil accumulates on granite slopes.

It is, therefore, only under rather severely arid conditions of climate that typical back-wearing—that is to say, parallel retreat of steep boulder-controlled slopes—takes place.[8]

Non-Granitic Landscapes

When non-granitic slopes are subject to the processes of back-wearing they retreat generally much less uniformly than is the case with granites, because they are in general more heterogeneous in rock structure than those of granite mountains.

> Their initial faces are worn back in the early stages of their degradation into irregular forms, in which ungraded rocky ledges . . . . alternate with graded detritus-covered slopes, slanting 35° or less. These graded slopes, on which it appears that irregular sheetfloods must be formed, pass by . . . . concave profiles to the detrital cover

of the piedmont slope.[9]

Mature Dissection

The back-wearing of steep rock slopes is not confined to mountain fronts retreating more or less parallel to simple tectonic boundary lines of initial blocks. Valley-side slopes and the sides of embayments or extensions of the pediment into the interiors of mountain ranges are similarly exposed to attack by the back-wearing processes.

Apart from the back-wearing of valley sides with little or no change of slope, which results in late survival of the steep declivities of youth, there is little room for difference in the general aspect of landscapes ravined and dissected to maturity by the ephemeral torrents of an arid region and those of semi-arid climates as already

8 *Loc. cit.* (4), p. 1361.
9 *Loc. cit.* (4), p. 1413.

described (Chapter III). Even the tendency of slopes strictly to maintain their youthful steepness as degradation proceeds seems to be confined to those on granite and other rocks which weather like granite, for according to Davis, the slopes of "non-granitic" mountains "are slowly reduced to lower and lower declivity."[10]

Though there is considerable similarity not only of drainage patterns but even of sculptured forms in areas of young to mature dissection developed under arid, semi-arid, and even humid climates (at least on terrains other than granitic), it does not seem possible that forms as characteristic of vigorously flowing rivers as incised meandering valleys should ever be developed under arid conditions. The presence of such features, as mapped by Schweinfurth in Egypt,[11] may indicate that a climatic oscillation towards humidity has occurred during the period in which dissection has been going on. Thus a Quaternary humid epoch, contemporaneous with the Glacial Period, has been invoked in order to explain relief forms in the Algerian Sahara and other parts of the North African deserts.[12] It does not seem necessary, however, to ascribe to such an epoch, which was perhaps relatively short, the whole development of the relief. Valleys already in existence may have been deepened and modified in form during a pluvial epoch, and some of the North African "relict" forms (developed by erosion controlled by a former climatic condition) may constitute only minor modifications of the general sculpture.

Mountain-front Embayments and their Extension

When desert mountains are fully mature, their valleys have been opened out to become mountain-front "embayments," which have steep side walls but broad flat floors. The valley floors assume the form of extensions of the constantly developing pediments or piedmont slopes back into the mountains, and have been opened out and are still being extended by back-wearing of the side walls. This is expressed by Bryan in the statement that the "projecting spurs" which separate embayments in the front of a "typical sierra"

[10] *Loc. cit.* (4), p. 1413.

[11] E. de Martonne, *Traité de géographie physique*, 2, 5th ed., Fig. 361, 1935.

[12] E. F. Gautier, The Heart of the Sahara, *Geog: Rev.*, 16, pp. 378-94, 1926; E. de Martonne, *loc. cit.* (11), p. 944.

in Arizona have "been produced by the cutting of canyons and the recession of slopes."[13]

After maturity has been attained, the embayments, or extensions of the pediment into the recesses of the mountains, grow gradually in area at the expense of ridges and spurs, which are narrowed and cut through, becoming later reduced to isolated island-like hills (Pl. VII, 2), and still later cut away altogether (Figs. 13, 18, 19, and 22).

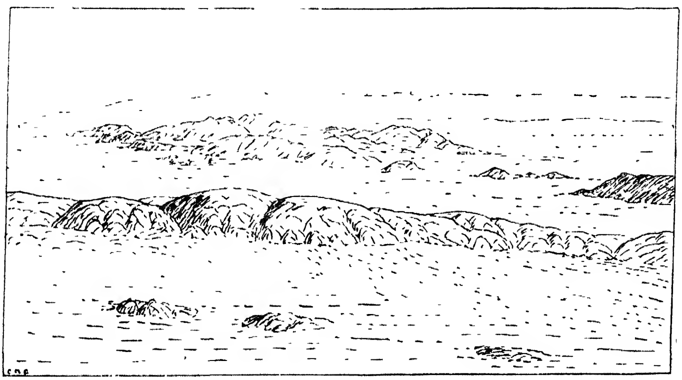

Fig. 19. Bahadas (and probably pediments also) surrounding the Löwenberge (gneiss) and (nearer) granite "inselbergs" in the desert of South-West Africa. (After E. Kaiser.)

Each isolated hill-remnant "retains the slope characteristic of the kind of rock, and gradually decreases in size" (Bryan). These disappearing spur-remnants cannot be regarded as homologous with all the "inselbergs" that surmount African plains (Chapters VII, VIII), but have been so named in some desert studies. Small spur-remnants are perhaps better termed "nubbins." This term was used originally by Lawson for the last remnants of a mountain range surviving along its crest as the range succumbs to destruction by desert erosion, but it is equally applicable in this homologous case. These, like summit remnants, survive for the most part in chance positions and may then be composed of rocks exactly similar to those in the parts of the spurs already destroyed by back-wearing.

[13] Kirk Bryan, *loc. cit.* (5).

Across the floors of mountain-front embayments disintegrated debris from the retreating rock walls along their sides and around their heads is transported by water, and erosion of some kind in which running water co-operates afterwards lowers the levels of the floors—just as it wears down the outer piedmont slopes. Davis has maintained, however, that there is no visible evidence that mountain-front embayments in the arid Mohave Desert are appreciably widened or extended by lateral stream corrasion.[14] Some critical studies by Bryan,[15] which have led him also to reject the hypothesis of lateral stream corrasion as the general cause of pediment extension, have been made at the sides of embayments. In embayments that are never traversed by large streams he finds "rill wash" (which includes sheetflood action) to be the only effective agency co-operating with the side-wall retreat that results from weathering. He finds such embayment floors concave. Where the floors are, on the other hand convex (fan-shaped) and large though ephemeral streams debouch in the embayments, he holds that some extension by lateral corrasion takes place.

According to an argument deduced by Davis[16] fan-form convexity is not decisive evidence on this point; for

> whether a dominant streamflood, after issuing from its mountain canyon at the head of an embayment, maintains itself in a narrow channel or broadens into a sheetflood, the graded detrital surface of the embayment down which it runs must have down-slope lines of essentially uniform declivity radiating from the apical angle of the embayment. The bay surface must, therefore, be slightly convex in cross profile, must be fan-shaped. An observer standing on one side should not see the other side.

Davis's examination of many embayments in both granitic and non-granitic mountains failed to reveal any side-wall undercutting such as would indicate that some enlargement by lateral corrasion had occurred. The evidence from non-granitic mountains, with their gentler slopes and general absence of sharp basal re-entering angle, is most significant (Figs. 20, 21). Con-

[14] *Loc. cit.* (4).

[15] Kirk Bryan, Processes of Formation of Pediments at Granite Gap, *Zeits. Geormorph.*, 9, pp. 125-35, 1935.

[16] *Loc. cit.* (4), p. 1368.

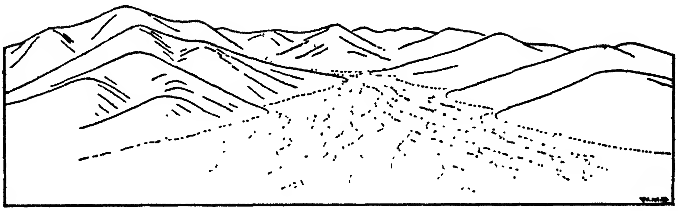

Fig. 20. Embayment in a "non-granitic" mountain in the Mohave Desert, California. (After Davis.)

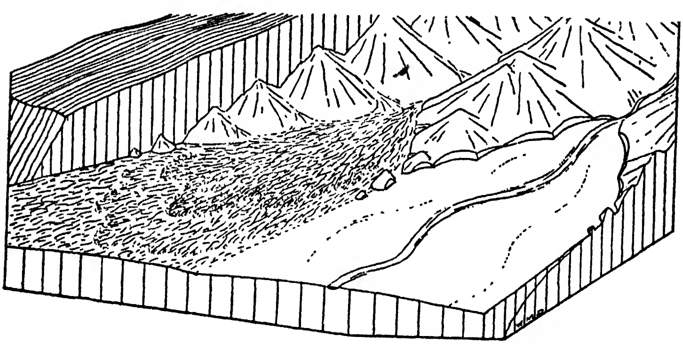

Fig. 21. "Contrasted features of embayments produced by back-wearing and by lateral streamflood erosion." (After Davis.)

trasted features of embayments as Davis found them (centre) and as he would have expected them to appear if lateral corrasion had been a dominant process (right) are shown in Fig. 21.

Coalescing Pediments

As a desert mountain range wastes away, two-way piedmont slopes may join up in "pediment gaps" (Sauer) across a main divide (Figs. 13, 19, 22, 23), which is from now on situated not on a ridge "but on a broad platform . . . the mountain pediment" (Bryan). Before this stage is reached, however, expansion of pediment embayments, or valley floors, takes place into "headwater

basins" (BRYAN), as a result of shortening of spurs between embayment branches as they are attacked by weathering and erosion on two sides. Residual portions even of main divides are at last reduced to nubbins, and then these are whittled away, so that in the early old-age, or senescent, stage of the cycle pediments, bare or concealed, coalesce to form a continuous surface.

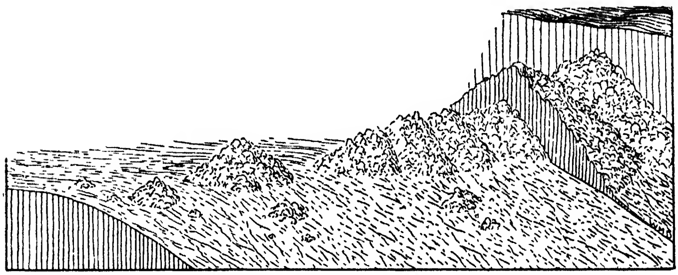

Fig. 22. Davis's diagram of "reduction of a granitic mountain to mounts, knobs, and nubbins." (After Davis.)

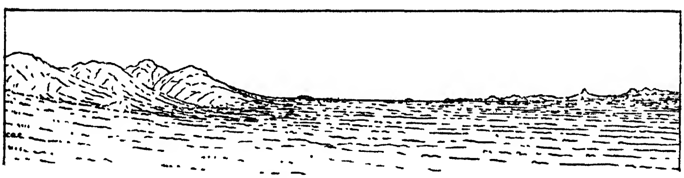

Fig. 23. Coalescing pediments on a divide 20 miles south-west of Needles, Mohave Desert, California. (Drawn from a photograph by Lawson.)

From analogy with peneplains of humid erosion the stage at which a continuous smooth (though as yet far from level) surface replaces former mountains might be termed old age. Slopes of coalescing pediments are still steep, however, at this stage as compared with those, for example, of great parts of the vast rock floor of Mongolia, the "Gobi erosion plane" (p. 17), which may have resulted from a combination of desert weathering and sheetflooding with the dry exportation of wind-borne dust continuing over a very long period. If such surfaces be truly *senile* deserts, those that still retain the strongly undulatory profiles of recently coalesced sloping pediments may be appropriately termed "senescent." Thick bahada accumulations may still underlie the lowest parts

of a senescent surface in the central and axial parts of initial basins; only where the surface exhibits its broad convexities of form is it a pediment or thinly veneered rock floor. Lawson names the stage the "panfan," to which term the objection has been raised that it fails to emphasise the fact that much of the surface is now a rock floor, that is to say, a bare or thinly veneered pediment. Bryan's conception of the form of a range after it is reduced to coalescing pediments is that it is either bluntly conical or, if initially elongated, "a tent-shaped ridge having a half cone at each end." Lawson also deduced that convex parts of his "panfan" surface would assume a ridge form in which the last-formed strips of rock floors asymptotic to, and emerging from beneath the feather edges of, the prevailing bahada slopes of the desert would meet at an angle. Davis, however, has found that senescent granitic mountains in the Mohave Desert have become true domes.[17] Instead of a slope conforming to a hyperbolic curve asymptotic to the nearly plane bahada slope he has found that the now-emergent rock floor has, and he has argued that it must have, a continuing convexity merging into a horizontal plane at a summit divide, where it may join an accordant surface approaching it by development from the opposite side of the range.

Desert Domes

Davis's explanation of domes found instead of cones, and arches instead of tent-shaped divides, on senescent desert mountains is based on a recognition that, on granitic rocks at least, a certain amount of "sheetflood erosion," to use McGee's term,[18] accompanies sheetflood transportation and co-operates with back-wearing by weathering in developing the pediment or bare-rock surface that occupies a proportionally large area of the landscape at this stage of the desert cycle. Thus the later-formed strips of the widening pediment are progressively lowered instead of being extended back as an approximately plane slope of transportation. "Bays and domes respectively represent earlier and later stages of sheetflood gradation; but in the earlier stages sheetfloods act chiefly as transporting agencies with a faint tendency to aggradation, and in the later stages they

[17] W. M. Davis, Granitic Domes of the Mohave Desert, California, *Trans. San Diego Soc. Nat. Hist.*, 7, pp. 211-58, 1933.
[18] See p. 56.

still act chiefly as transporting agencies, but with a faint tendency to degradation on the higher, convex slopes."[19] The pediment is not now covered and protected, as it is in earlier stages in desert basins, by a continuous layer of debris in transit down the piedmont slope from the mountains, as the supply of this has shrunk. The pediment is, at least occasionally, bare and subject to weathering, and sheetflood erosion on it consists not to any great extent of actual abrasion, but in the main of the mere removal from it of the debris of dry weathering—the process of "rock-floor robbing" (DAVIS), which has been referred to on an earlier page (p. 56). The sheetfloods "begin to rob the cover of some of its detritus or the rock floor of some of its disintegrated grains, with which to satisfy their excess of energy; and thenceforward the conditions for the development of an increasingly rectilinear profile can no longer obtain."[20]

When the stage is reached at which rock-floor robbing begins, or at which diminution in area of frontal slopes of vanishing mountains has proceeded so far that sheetfloods no longer derive from them a load of debris equal to their carrying capacity, the extreme up-slope limit of the extension of the feather edge of the bahada veneering the pediment has been attained. Thenceforward robbing by sheetflood erosion becomes progressively more effective as the supply of debris available for transportation becomes smaller; and at the same time diminishing load demands a gradient of diminishing steepness for its sheetflood transportation. Thus when the last nubbins of the mountains are consumed and the rock floor extends to the summit divide it has become horizontal, and a dome or arch has developed if a similar arching rock floor developing from a pediment on the other side of the range approaches the summit divide *at an accordant level.*

The Cima granite dome (Fig. 24), in the Mohave Desert is the most perfect example of such a dome that has been described.[21] The upper 600 feet of the dome consists of bare rock with slopes increasing downward from zero to 4°. Published photographs[22]

[19] W. M. Davis, *loc. cit.* (4), p. 1391.
[20] W. M. Davis, *loc. cit.* (17), p. 220.
[21] W. M. Davis, *loc. cit.* (17), (4).
[22] W. M. Davis, *loc. cit.* (4), Pl. 1; (17), Pl. 12.

indicate the smooth, convex perfection of the domed summit, though a faulty topographic map makes it appear conical.[23]

The dome form, as pointed out earlier, is senescent but not senile. Together with fringing bahadas it may present a relief of several thousand feet and slopes of 1 in 10. "The graded dome is evidently not a final form. The very processes by which its convexity is initiated continue after its completion to degrade it to lower and lower convexity."[24] As in the case of further degradation

Fig. 24. The Cima Dome, California. (From a photograph by Professor E. Blackwelder.)

of the hills of a fully mature surface of normal erosion to the more subdued forms of a peneplain, reduction of steepness of graded rock floors in the desert implies most rapid lowering of the surface where declivities are least—that is, on broadly convex and approximately horizontal summits—an "apparent paradox" (Davis), which, however, seems to be a fact of nature.

Very smooth summit convexity such as will produce a perfect dome is not to be expected in deserts on rocks other than granitic; for other terrains not only lack the areal homogeneity of granite, but fail also when attacked by dry weathering to provide the uniformly fine detritus the presence of which controls the finely-balanced floor-robbing processes responsible for the production of smooth convexity.

Some irregularly domed residuals in the Mohave Desert, consisting of non-granitic rocks and even in some cases of granite, present in detail a multitude of huddled low irregular hillocks and must be explained as developed by some process of less regular down-wearing in contrast with the combination of pediment-extension and back-wearing which has resulted in converting some

[23] W. M. Davis, *loc. cit.* (17), Fig. 18; see also K. Bryan, "The Retreat of Slopes" in Symposium: Walther Penck's Contribution to Geomorphology, *Ann. Ass. Am. Geog.*, 30, pp. 219-84, 1940.

[24] W. M. Davis, *loc. cit.* (17), p. 226.

granite residuals into smooth domes, but only under the most favourable conditions.[25]

Failure of dome development in cases where all the favouring conditions do not combine makes broadly domed and arched summits rather exceptional forms in the senescent peneplain of arid and semi-arid erosion. Bryan notes a predominance of "tent-shaped" ridges and conical forms[26] in the senescent landscape. The failure of summits to assume an ideal convexity where composed of non-granitic rock is thus explained by Davis:

> The upper parts of these residual forms show little tendency to develop convex slopes except just over their tops, presumably because the somewhat coarser detritus [as compared with granitic debris] . . . prevents the degradation of the upper slopes to a diminishing declivity. These mountains therefore show in the penultimate stages more ridge- and cone-like forms than granitic mountains do.[27]

Discordance of Level in Coalescing Pediments

Accordance in level of piedmont slopes approaching a mountain crest from opposite sides can occur only fortuitously where the slopes are controlled by local base-levels in separate basins of internal drainage; but slopes leading down by different routes to the some playa may be expected, according to Davis's reasoning, to meet accordantly.[28] If rock floors developing from opposite sides of a range approach their meeting-place discordantly (at different levels), on the other hand, a scarp will be formed there, descending abruptly from one pediment to the other, leaving the summit to be lowered still farther by a continuation of the back-wearing process in the face of the scarp. Meanwhile the symmetry of the dome is spoiled. Some "scarped half-domes" and other forms produced by this irregular method of dome development occur in the Mohave Desert (Figs. 25, 26).

[25] W. M. Davis, *loc. cit.* (4), pp. 1388, 1393.

[26] Kirk Bryan, The Formation of Pediments, *Rep. XVI Internat. Geol. Congr.*, 11 pp. 1935; *loc. cit.* (23).

[27] W. M. Davis, *loc. cit.* (17), p. 230.

[28] *Loc. cit.* (4), pp. 1372-3.

Adaptation of Penck's Hypothesis of Slope Retreat to Pedimentation

For comparison with the theories of desert erosion set out in this and earlier chapters one may glance at the pedimentation hypothesis developed in explanation of mountain sculpture in southern Arizona by Sauer[29] in terms of W. Penck's system of geomorphic study.

According to the general theory, long-continued parallel retreat of slope elements accompanied by replacement and continuation of lower slopes by more and more nearly level slope elements under

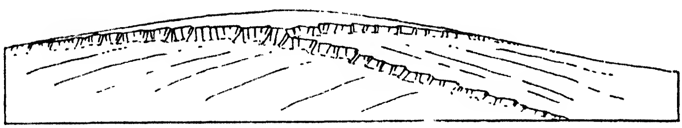

Fig. 25. Discordant dome surfaces draining to different basins and separated by scarps. (After Davis.)

conditions of stationary base-level (or extremely slow lowering of base-level) develops in any climate a concave mountain-front profile of which a pediment forms a relatively large part. This process is one in which "denudation" (in the German sense) is dominant, and extensive pediment development requires freedom from interference by stream work ("erosion").

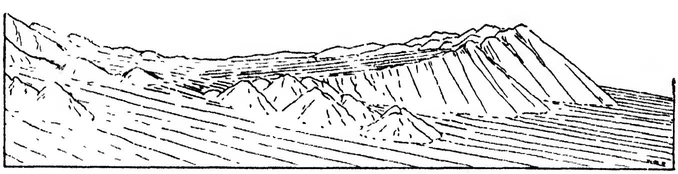

Fig. 26. "Unsymmetrical degradation in the Bullion Mountains, looking north-west." (After Davis.)

In the Chiricahua area of south-eastern Arizona and northern Sonora, described by Sauer, semi-aridity now prevails, but this author regards the landforms as mainly relict—that is, he ascribes

[29] C. Sauer, Basin and Range Forms in the Chiricahua Area, *Univ. Cal. Publ. in Geog.*, 3 (6), pp. 339-414, 1930.

the pedimentation to a former more arid period in which not only were slowly-extending pediments immune from modification and destruction by stream erosion, but also the process of "denudation" was extremely vigorous, owing to absence of all vegetation facilitating a somewhat mysterious "mass transport" of debris down even very gentle slopes. This removal of waste exposed bare-rock surfaces to weathering, and continued removal of the debris resulted in rapid parallel retreat of all slope elements. Sheet-flood transportation is admitted as performing a share of the work of down-slope removal of waste across the pediment.

This theory, though expressed in different terms has much in common with, and is in part based on, Lawson's deductions regarding mountain-front retreat; but it places the emphasis on those cases in which the smoothly concave transitional curve observed by Davis in the case of non-granitic mountains (p. 60), connects the steep mountain face with the pediment. "If there is in this region an angular contact between mountain pediment and mountain flank it is exceptional,"[30] is Sauer's verdict.

[30] C. Sauer, *loc. cit.* (29), p. 368.

CHAPTER VII

African Inselbergs and Plains

PROMINENT steep-sided residual hills and mountains rising abruptly from plains make a landscape type rather common in Africa. The residuals are generally bare and rocky; large and small, isolated and in hill and mountain groups, they are surrounded by lowland surfaces of erosion that are generally true plains (as distinguished from peneplains). These are of wide extent and small inclination. The landscape type, termed by Bornhardt[1] the "inselberg landscape" (*Inselberglandschaft*) (Fig. 27), is well exemplified in the savana belts north and south of the equatorial rain forest in both West and East Africa, and is generally regarded as developing in response to a climatic control.

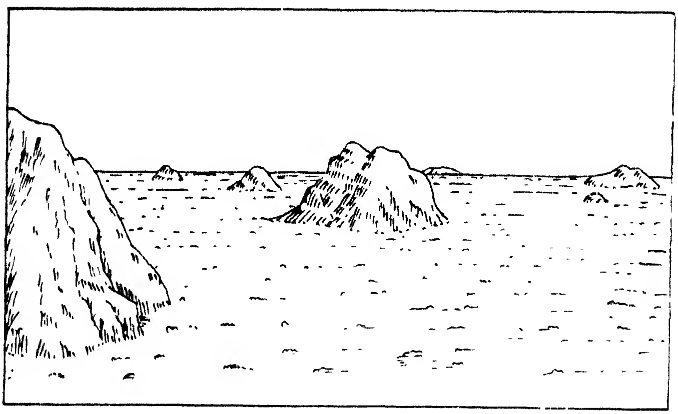

Fig. 27. The "inselberg landscape" of Mossamedes, South-west Africa. (After Peschuel-Lösche and Passarge.)

Pediment landscapes (mature surfaces of semi-arid to arid erosion) in North America have been included also in the category of inselberg landscapes by Waibel,[2] but that author has had in mind for comparison with these the landscapes of only the arid districts

[1] W. Bornhardt, *Zur Oberflächengestaltung und Geologie Deutch-Ost-Afrikas*, Berlin, 1900.

[2] L. Waibel, Die Inselberglandschaften von Arizona und Sonora, *Jub. Sonderb. Gesells. Erdk. Berlin*, pp. 68-91, 1928.

of South-west Africa (Fig. 19), from which, though they have been classed with them by some authors, the "landscapes" of the savana belts seem in reality to be distinct.

Davis[8] also has recognised some resemblance between American pedimented and African inselberg landscapes, but he has pointed out important differences which are summarised in the statement:

> Similar but more nearly level and much more extensive rock floors, here and there surmounted by abruptly rising residual mountains . . . . occur in the drier parts of Africa.

All gradations may perhaps be found between these two types, but the differences between the pedimented and the African savana-climate landscapes where they are typically developed must be regarded as sufficiently great to place the latter in a different category of landforms. For purposes of geographical landscape description at least they are better kept apart; but, on the other hand, when the object of study is genetic comparison and the recognition of analogies and homologies their position may well be side by side in classification, perhaps as variants of a common landscape assemblage which is distinct from that developed in the normal geomorphic cycle in extratropical humid regions. No doubt all these extremes are linked by intermediate forms.

The Savana Landscape

The obvious differences between characteristically pedimented landscapes developing towards peneplains of semi-arid erosion, on the one hand, and typical examples, on the other, of the African type of "inselberg landscape," or, as it may perhaps be less ambiguously called, the *savana landscape,* resolve themselves almost entirely into differences of slope on the plains which border and surround the mountain residuals; for in both the assemblages smooth plains are characteristically present in the mature and post-mature stages of the development cycle.

Such differences of declivity on piedmont slopes must depend chiefly on differing rates of erosion on the catchment areas that supply detritus. These in turn depend on major relief (in some regions initial relief and in others depth to which dissection of the

[8] W. M. Davis, Rock Floors in Arid and in Humid Climates, *Jour. Geol.,* 38, pp. 1-27, 136-158, 1930 (see p. 6).

landscape extends in the stage of youth) and also on terrain and rate of weathering as governed by climatic conditions. These latter control the volume and grade of the debris which must be carried away by the rivers. The average slopes on the plains depend in part also on the rainfall regime, however, as this determines the mode and rate of removal of rock debris; for the slopes of river-made and flood-made plains, whether they are cut by erosion or built by deposition, depend on the ratio subsisting for the time being between the volume of waste in process of removal by water transport and the volume of water available for the task of removing it.

Gentle slopes on plains of erosion which, by whatever means they are extended backward at the expense of mountains at their rear, have been cut to their present gradients by the action of water streams or floods may indicate, therefore, either that the supply of rock debris for transport across the plain is meagre or that the agencies available for such transportation are particularly efficient.

Though this landscape assemblage, as noted above, is characterised especially by its widespread, nearly level plains, the "astonishing" extent of which has been insisted on by Passarge[4] in his generalisations, the sharp contrast subsisting between the plains and mountain residuals which stand above them has focussed more attention on the residuals. So prominently do these island-like residuals (hillocks, hills, and even mountains and mountain clusters) stand forth that their forms have become special objects of study and have monopolised the attention of many students of the landscape type. The sharp contrast between the steep side slopes of even the smallest inselbergs and the flatness of their surroundings makes them conspicuous; Passarge has more than once likened their appearance to that of small islands in the ocean, and the same simile has been employed by Holmes.[5]

African savana or inselberg landscapes, most of which stand at elevations of 1000 to 2000 feet, are still in course of development at their present levels. They are generally, that is to say, for the most part undissected, and their rivers have not undergone rejuvenation; their surfaces must still be under the control of the local base-levels.

[4] S. Passarge, *Panoramen afrikanischer Inselberglandschaften*, p. 9, 1928.

[5] A. Holmes, Rocks of the District of Mozambique, *Quart. Jour. Geol. Soc.*, 74, p. 34, 1919.

Inselbergs of the Savana Landscape

The residual hills and mountains of the savana regions were termed inselbergs by Bornhardt,[6] who described them as "rounded domes" alternating with "sharp pinnacles [Fig. 28] and broad, smooth turtlebacks" of heights ranging up to more than 500 metres

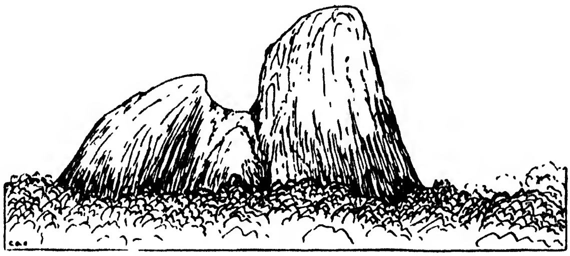

Fig. 28. Matshemba Inselberg, East Africa. (After a sketch by Bornhardt.)

above the surface of the plains around them. His first impression of the *Inselberglandschaft* was as follows:

> We now entered upon a landscape of very unusual character, remarkable because, while for about 150 kilometres in an air-line its altitude varied only between very narrow limits, there rose above the wide plain innumerable peculiarly-shaped hills, resembling islands, steep and rocky and several hundred, yes in certain cases more than 500, metres high . . . . Neither to the north nor to the south is any end to the landscape to be seen. Even from the summit of a hillock nothing but the plain and the island mounts rising above it was in sight. The higher we ascended the greater the distance at which such mounts came into view, their bases still lying below the horizon.[7]

Passarge also made use of the term "inselberg" for these mounts when he in his generalisations made known to the world the "inselberg landscape" as a characteristic African assemblage.[8] It is employed also by Obst,[9] who has re-described the landscape of the

[6] *Loc. cit.* (1).

[7] Translation by Bailey Willis.

[8] S. Passarge, Die Inselberglandschaften in tropischen Afrika, *Naturwiss. Wochens.*, 3, pp. 657-665, 1904.

[9] E. Obst, Das abflusslose Rumpfschollenland in N-O. Deutsch-Ostafrika, Teil 2, *Mitt. Geogr. Ges. Hamburg*, 35, pp. 16 ff., 1923.

classic East African locality. Krebs[10] has more recently termed the residuals "tropical" inselbergs, apparently because the unqualified term *Inselberg* has been used by Walther Penck[11] with such a wide connotation for any steep-sided hill isolated by circumdenudation that it has lost its former more restricted meaning. Penck's theories require that residuals of similar steep-sided form shall rise above any undisturbed peneplain (*Endrumpf*). In English, however, the term "inselberg" without qualification remains good and may be restricted in its use to forms of like nature to those so called by Bornhardt.

Bailey Willis[12] extends the meaning of the term to include as inselbergs all tors, kopjes, and geomorphic monoliths; but, on the other hand, he would wisely restrict it by excluding all residual mountains and hills that do not conform in their configuration to Bornhardt's East African type. That is to say, he deplores inexact use of the term in the general sense of "monadnock" and almost despairs of restricting usage to the original meaning. Thus he goes the length of suggesting a new term "bornhardt" to replace "inselberg." In common with some others, however, Willis has lost sight of the fact that true "inselbergs" (or "bornhardts") rise from plains; and the extension of the inselberg category to include all giant tors and monoliths[13] is unfortunate. Such forms are not in most cases residuals in the sense that monadnocks are. True inselbergs, however, may be considered a species of the genus monadnock.

Inselberg-making Terrains

The best known examples of true inselbergs and "inselberg landscapes" are situated in the terrains of resistant crystalline rocks in areas "over which long continued denudation has exposed the basement rocks of the African continent, rocks which, as in Mozambique, consist of banded and foliated gneisses, accompanied

[10] N. Krebs, Morphologische Beobachtungen in Südindien, *Sitz. Ber. Pr. Ak. Wiss.*, Ph-M. Kl. 23, p. 710, 1933.

[11] W. Penck, *Die morphologische Analyse*, pp. 157-161, 1924.

[12] B. Willis, *East African Plateaus and Rift Valleys*, Carnegie Inst., Washington, 1936.

[13] The monoliths, or "sugarloaves," of the granite-gneiss terrain of Brazil have recently been termed "inselbergs" by both Willis (*loc. cit.* (12)) and F. W. Freise (Inselberge und Inselberglandschaften im Granit-und-Granitgneissgebiete Brasiliens, *Zeits. Geomorph.*, 10, pp. 137-168, 1938).

by crystalline schists and limestones, and penetrated by the later granites and pegmatites."[14] A predominantly granite-gneissic terrain, though obviously favourable, is not quite necessary however, for the development of inselbergs. Thus, in south-western India Krebs[15] has found the typical "inselberg landscape" developed in

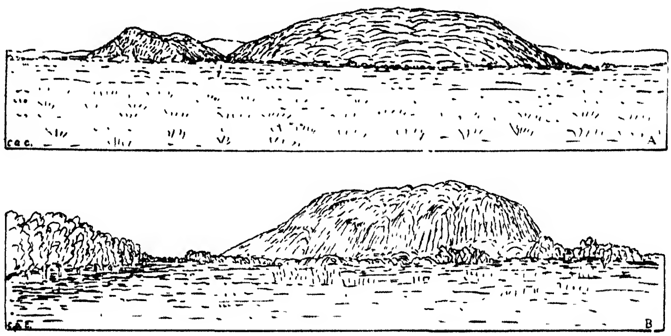

Fig. 29. A: An inselberg (of greenstone) standing above a plain which is in course of development in the current cycle, West Pilbara district, Western Australia. (Drawn from a photograph.) B: An inselberg at Krishnagiri, Madras, India, on granite-gneiss terrain. (After a photograph by Krebs.)

basalts as well as schists, quartzites, and granite-gneissic rocks; and in north-western Australia inselbergs most commonly survive on a greenstone (basic igneous) terrain (Fig. 29A), while outcrops of granite, owing to greater susceptibility to weathering, are worn away more evenly.[16]

Passarge[17] and Falconer[18] have held that inselberg residuals are commonly, though perhaps not invariably, different in rock composition from the surrounding plains. Cushing[19] also has noted a localisation of the monadnocks (which are apparently true inselbergs) on the coastal lowland at the base of the Eastern Ghats, in India, on quartzite outcrops in a metamorphic terrain.

[14] A. Holmes, *loc. cit.* (5), pp. 89-90.

[15] *Loc. cit.* (10), p. 712.

[16] J. T. Jutson, Physiographical Geology of Western Australia, *W. A. Geol. Surv. Bull.*, 61, 1914.

[17] S. Passarge, Rumpffläche und Inselberge, *Zeits. Deutsch. Geol. Gesells.*, 56 (Protokol), pp. 195-213, 1904.

[18] J. D. Falconer, *Geology and Geography of Northern Nigeria*, 1911.

[19] S. W. Cushing, The East Coast of India, *Bull. Am. Geog. Soc.*, 45, pp. 81-92, 1913.

Holmes,[20] on the other hand, comes to the conclusion that such a difference of rock character is exceptional; Gillman[21] also regards occasional difference as especially worthy of mention as a departure from the general rule.

If it should be established that a rock boundary is situated exactly at the base-line of an inselberg, as Passarge[22] believes to be the case in many examples, the conclusion is inescapable, in the case of nearly vertical boundaries such as those of intrusive rocks, that the inselberg has not suffered—and is, therefore, immune from—reduction in area by any back-wearing process. On the contrary it will be rooted on the structure of the rocks as firmly as any hogback in a mature landscape, and its survival as a landform must be due to progressive down-wearing of surrounding plains proceeding at least as rapidly as the down-wearing of the salient inselberg. Were this the general case it would be necessary to explain the wearing down of plains themselves underlain by hard rocks and many thousands of square miles in extent as rapidly as a few prominent rocky knobs of somewhat different rock character are wasted away and worn somewhat lower, but not destroyed, under the attack of physical and chemical weathering.

Such a paradoxical state of affairs has been fully accepted by Willis as the true course of inselberg history. As they are explained by him inselbergs have survived through many cycles of erosion—progressively increasing in relief, indeed, in successive cycles—so that they must be regarded as defying the elements since the Palaeozoic era. Willis ascribes their origin to a special immunity from the weathering which has affected their surroundings to a very considerable depth during each successive cycle.[23]

"At first," he says, "there is but a hummock or low kopje of residual boulders; but if the land mass is elevated and the plain lowered by erosion, the naked residual may grow to the stature of an impressive inselberg."[24]

[20] A. Holmes, *loc. cit.* (5), p. 92.

[21] C. Gillman, Zum Inselbergproblem in Ostafrika, *Geol. Rd.,* 28, pp. 296-297, 1937.

[22] S. Passarge, *Physiologische Morphologie,* p. 54, 1912; *loc. cit.* (1928), p. 6.

[23] B. Willis, *loc. cit.* (12), especially pp. 119, 127.

[24] *Loc. cit.* (12), p. 127.

According to this hypothesis (if it could be maintained) it would be easy to account for the absence of talus such as might, if present, obscure the re-entering angle between the side slope of an inselberg and the surrounding plain. If the inselberg is not wasting away, no talus is produced. It has been frequently observed, however, that the steep bare-rock scarps of inselbergs are affected by large-scale exfoliation (Fig. 30). Though they waste but slowly they cannot be considered immune from destruction.[25]

The observation, previously quoted, that inselbergs do not necessarily differ in any marked degree in rock character from the rocks under the plains around them agrees very well with the hypothesis that the residuals are in process of reduction in size (in area especially) by the retreat of the steep scarps which form their sides.

The Scarp-foot Nick

It is characteristic of inselbergs that their lower slopes are very steep (Figs. 29, 30), and in many cases these scarps are smooth and are scarcely broken at all by gullies. In a good many cases they are convexly rounded and are obviously wasting away (though slowly) as a result of large-scale exfoliation from the exposed surface (Fig. 30). A sharp angle (termed *Knick* by Passarge) is characteristically present between the scarp bounding a residual and the plains surface below it, and this re-entering angle in the landscape profile is rarely masked by any considerable accumulation of rock debris. Indeed, so free of talus and so clearly defined is the "nick" in some examples, Passarge remarks, that one's hand may be placed in it.[26]

The absence of talus is suggestive of wind scour as the agent chiefly responsible for the removal of fallen debris, but it is probable

[25] It is worthy of note that the steep sides of monolithic domes or "sugarloaves" in the tropical rain forest of Brazil, which have been placed by Willis (*loc. cit.* (12)) in the same category as East African inselbergs, and which are now classed as inselbergs by Freise also (*loc. cit.*), are found by the latter investigator to be by no means indestructible. Among the agencies reducing them to smaller dimensions of which he finds some evidence he describes a secular cycle of chemical weathering which includes stages of gradual development of soil, afforestation, soil deterioration, deforestation, and soil erosion, the cycle ending as it began with the exposure of bare rock on gneiss and granite slopes from 35° to 52° in steepness.

[26] *Loc. cit.* (22) (1928).

that this explanation has been applied too widely, especially in textbooks. Whatever be the method of its removal, some disintegrating talus is still to be found at the bases of most inselberg scarps (Fig. 30).

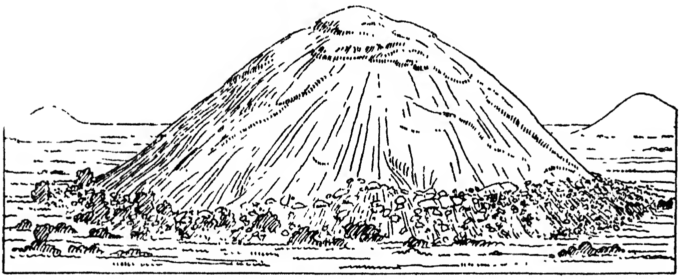

Fig. 30. An inselberg of granite in the Kilba Hills, Northern Nigeria. (Drawn by W. M. Davis from a photograph.)

"Inselberg landscapes" are distinguished from late-mature to senile surfaces of normal erosion essentially by the steepness of the side slopes (actual scarps) of the residuals and by the absence of any broad concave slopes transitional from these to the plains below.

The Landscape Cycle in Inselberg Regions

In well-known examples of inselberg-and-plain landscapes the proportion of the area of plains to inselberg residuals is high, and, as noted above, there are no features transitional between these two elements of the landscape. The same high proportion is not found, naturally, in landscapes of less advanced development; these have more restricted areas of plains and more extensive residual mountain areas. Such landscapes are mature in the cycle which leads to the development of the senescent to senile surfaces with widely extending plains which have attracted most attention. In Mozambique, though near the coast only "isolated hills and linear series of hills of the inselberg type rise up abruptly from the plateau," and each "bare rounded inselberg of gneiss stands alone like an island," inland "the small inselberge increase in height and numbers and grow together in imposing linear series and towering mountain clusters"[27] (Figs. 35, 36). In this (westerly) direction the plains increase in elevation with an average gradient of about ten feet per mile.

[27] A. Holmes, *loc. cit.* (5), p. 34.

A similar transition is recorded by Passarge around the Mandara Mountains of Adamawa and Northern Nigeria. The mountains themselves are only maturely dissected, but their outlying spurs have been isolated as large inselbergs and inselberg groups, while farther from the mountain cluster, especially westward, as shown in Passarge's panoramas[28] and also recorded by Falconer[29] (Fig. 30), early old age in the landscape cycle has been attained. Here for hundreds of miles there are merely scattered isolated inselbergs dotted over continuous plains of wide extent. Several hundred miles westward, in Hausaland, the senile landscape as described by Falconer is "an open plain reaching to the horizon, partly covered with sands, partly exposing bare rock, with gentle undulations following one another in endless succession. Geological processes seem to have come to a standstill. The rivers follow poorly defined, shallow, soil-covered depressions in the plain. Here and there a group of boulders, a long turtleback, or a knob of granite rises."[30]

Farther westward still, beyond the Niger, however, on the extensive upland plains above the 2000-feet contour around Wagadugu in the hinterland of Dahomey, where there is a flat watershed between the Niger basin and the Gulf of Guinea, planation is again less complete and inselbergs rise to heights of approximately 1000 feet above the plains.[31]

A survey of the inselberg-landscape (or savana) cycle is incomplete if it does not embody some speculation as to initial forms and the stages such landscapes have passed through in their youth. Without allowing too free a rein to the imagination one may safely follow such authorities as Jaeger and Jessen[32] and trace the African landscapes back to a hypothetical stage of youth differing but little, if at all, from that of the normal cycle in a similar terrain when it is initiated in a similar way. Briefly, if the cycle is inaugurated by a fairly uniform uplift of a former land surface of small relief,

[28] *Loc. cit.* (22) (1928).

[29] *Loc. cit.* (18).

[30] Paraphrased by W. M. Davis, *loc. cit.* (3), p. 8.

[31] H. Hubert, *Mission Scientifique au Dahomey*, p. 121, Paris, 1908.

[32] F. Jaeger, Die Oberflächenformen in periodisch-trockenen Tropenklima mit überwiegender Trockenzeit, *Düsseldorfer. Geogr. Vortr.*, 1927; O. Jessen, *Reisen und Forschungen in Angola*, Berlin, 1936.

there will be developed systems of streams with steep-sided youthful valleys and other normal features. The same similarity will persist in a general way in early maturity when the uplifted surface has been dissected into ridges and spurs, all steep-sided, but there is not as yet any extensive development of valley-floors and river-cut plains in the landscape.

Deductive elaboration of the features of a landscape cycle inaugurated by movements of differential uplift might be attempted, but seems unnecessary. Within the boundaries of each uplifted block, arch, or dome of the initial surface dissection and landscape development would proceed on the same general lines as in a region broadly uplifted.

The Savana Landscape outside Africa

Passarge has referred to the occurrence of "inselberg landscapes" in Guiana, Ceylon, Further India, and Australia.

In the savana-climate belt south of the Parima Mountains of Guiana there is a low-lying flat region in which the divides are very indefinite between affluents of the Orinoco and the Amazon. There is, indeed, a remarkable natural canal (Casiquiare Canal) which connects the Orinoco River with the Rio Negro. Near this the plains are very extensive, and Passarge has reported that remnants of dismembered former divides rise out of the confluent grass-covered plains as island-like "turtleback" hills and low (mostly tree-clothed) granite crags, knobs, and single huge blocks.[33]

The plains here have been described as "so level that very little definite run-off has been established," and water channels show no appreciable currents. There is a characteristic contrast in a short distance, however, between these plains and steep and almost wholly inaccessible scarps (not structural escarpments) which bound the Cerro Duida. This mountain is a great peneplain-topped inselberg (or so it appears) composed of folded sandstone strata; it has a relief of 6000 feet and an area of 250 square miles. The scarp-foot nick around it is not quite sharp, and a narrow sloping pediment seems to be present around the mountain.[34]

[33] *Fide* K. Sapper, *Geomorphologie der feuchten Tropen*, pp. 116-117; 1935.

[34] Based on the description by G. H. H. Tate and C. B. Hitchcock, The Cerro Duida Region, *Geog. Rev.*, 20, p. 38, 1930.

Over a considerable portion of the Guiana region the terrain rather closely resembles that of typical African examples;[35] and on such a terrain 400 miles east of the Cerro Duida the flat savana district of the Rio Branco valley in northern Brazil is described as "generally level, but there are slight depressions which, coupled with an imperfect drainage system, give rise to extensive swamps." It is stated also that "in every direction the land is ancient peneplain with here and there granite bosses projecting through its surface,"[36] which strongly suggests that here is a good South American example of a true "inselberg landscape."

The Ceylon example to which Passarge refers is perhaps almost continuous with a belt along a great part of the east coast of

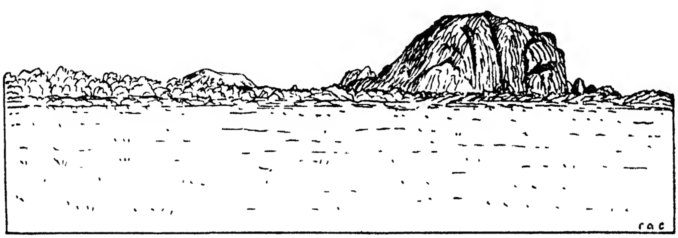

Fig. 31. Inselberg and plain near Madura, southern India. (From a photograph by S. W. Cushing.)

peninsular India on the dry coastal strip fringing the Eastern Ghats. The objective description of the features of this belt given by Cushing[37] leaves little doubt of the presence of the savana landscape. Though Cushing, who is followed by Johnson,[38] describes the forms as those of a plain of marine denudation with high, cliffed residual islands, his account of these latter, which is supported by diagrams and photographs (Figs. 31, 32), brings out their resemblance to typical inselbergs.

[35] D. W. Bishopp, Geomorphology of British Guiana, *Geol. Mag.*, 77, pp. 305-329, 1941.

[36] G. H. H. Tate, Notes on the Mount Roraima Region, *Geog. Rev.*, 20, p. 55, 1930.

[37] S. W. Cushing, The East Coast of India, *Bull. Am. Geog. Soc.*, 45, pp. 81-92, 1913.

[38] Douglas Johnson, *Shore Processes and Shoreline Development*, pp. 230-231, 1919.

Beach features that have been reported on this low-lying Indian plain may be ascribed to a temporary invasion by the sea. The way in which rivers pass in convenient gaps between inselbergs aligned (as described by Cushing) on resistant rock belts (Fig. 32) suggests that the gaps are river-made. It is impossible to believe that they have been cut fortuitously by marine erosion through the resistant

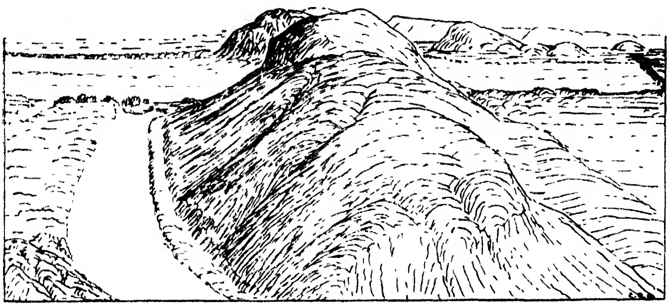

Fig. 32. A group of inselbergs traversed by the Kistna River at the base of the Eastern Ghats. A structure-controlled line of inselbergs (centre) is crossed by the river (from right to left) in a narrow gap which almost certainly is a river-cut gorge. An irrigation canal in the left foreground is artificial. (From a photograph by S. W. Cushing.)

ridges. It is significant also that the rivers which cross these plains find their gradients exactly suited to their needs.

Other Indian examples of the "inselberg landscape" have been described by Krebs.[39]

In the granite terrains of the Malayan region Credner[40] records the presence of plains extensively eroded across the granite, from which inselberg-like mounts and ridges stand out. He ascribes the forms to the effects of alternation of very wet summer and drier winter conditions in the monsoon climate. It seems doubtful, however, whether the landforms of this moist jungle-clad region can be differentiated from those of equatorial rain forests. Some of the features described may result from valley aggradation.

In the north-eastern interior region of Australia (western Queensland and part of South Australia especially) there are vast laterally

[39] *Loc. cit.* (10).

[40] W. Credner, Das Kräfteverhältnis morphogenetischer Faktoren und ihr Ausdruck im Formenbild Südostasiens, *Bull. Geol. Soc. China,* 11, p. 17, 1931.

confluent river plains, broadly floored with shallow alluvial deposits, over which dwindling intermittent streams fed by scanty and uncertain north-west monsoon rains make their way in widely braided channels down very slight gradients.[41] Some are members of the Murray system draining to the Southern Ocean, some discharge to the Gulf of Carpentaria, and some lose themselves in the direction of Lake Eyre in a vast low-lying arid central region in which any rise of local base-level as a result of alluviation is prevented by aeolian exportation of dust.

The low gradients of the plains of these rivers are related to the exiguous supply of waste (all fine-textured alluvium) which they derive from the very shallow dissection now in progress of an old-from-birth peneplain—a surface which owes its character to uplift of quite small measure affecting a weak-rock terrain and extending through a very long period, though occurring perhaps intermittently and being accompanied by widely fluctuating conditions of rainfall.

Over a vast area low mesas and buttes, which stand above the level of the river plains, are capped by a hard lateritic residue on the now dissected peneplain of which they are remnants. These residuals, the relief of which is generally less than 100 feet, might perhaps be correctly described as tabular inselbergs. Published descriptions do not convey the impression, however, that lateral planation by the rivers of the region is an important agency in extending the plains at the expense of the "inselbergs." The presence of widely-spreading aprons of debris recognisably derived from the escarpments of the residuals suggests, at least in some cases, on the other hand, that the process most active in the development of plains in this region is "back-wearing" accompanied by sheetflood transportation of debris over pediments of very low gradient.

Whether the hard-rock ranges in northern Australia, which retain considerable mature relief, are to be regarded as now undergoing dissection in a cycle of normal erosion, of pedimentation, or of inselberg-and-plains development has not been fully investigated or discussed; but it is clear that river erosion has played an important

[41] C. T. Madigan, The Simpson Desert and its Borders, *Jour. and Proc. Roy. Soc. N.S.W.*, 71, pp. 503-535, 1938; F. W. Whitehouse, Studies in the Late Geological History of Queensland, *Univ. of Q. Papers, Dep. of Geology*, Vol. 2, No. 1, pp. 1-74, 1940; F. W. Whitehouse, The Surface of Western Queensland, *Proc. Roy. Soc. Queensland*, 53, pp. 1-22, 1941.

part in the development of the relief forms of the ranges. This is manifested by the rather common occurrence of transverse gorges which cross prominent strike ridges—gorges which have been explained variously as superposed and antecedent.

Transition to other Landscape Types

In nature every intermediate member must be somewhere discoverable of a series of landscapes transitional between those in which typical inselbergs and plains are developing and those of the normal landscape cycle. So also must there be a transition to the pedimented landscape. Krebs[42] has found, indeed, that in southwestern India, a region of alternating dry and wet seasons, an extensive belt characterised by the "inselberg landscape" lies between the line of 50 inches rainfall, beyond which are humid-climatic forms, and that of 24 inches, below which figure he recognises a transition to landscape forms characteristic of arid regions. In the Concan district of the western coast, however, a rainfall greater than 50 inches is compensated for by an exceptionally long dry season, and so typical inselbergs are present.

In making such comparisons it must be remembered, however, that even in the savana climate the scarp-foot nick of inselbergs is not well developed in weak-rock terrains.

Another source of difficulty that has rarely been discussed at length arises out of the fact that the landforms produced by humid erosion in hot rain-forest climates differ very considerably from those of temperate zones, though the eventual result may be the production of similar peneplains in both cases. Hot and wet tropical conditions such as prevail in rain-forest regions throughout the year favour enormously rapid chemical weathering of almost every kind of rock and the development of actual flow movements of the saturated products of advanced rock-decay. This has been observed to affect a layer below the superficial zone which is more or less securely anchored by roots, and there is thus a streaming of mud and accelerated creep of saturated soil which resembles Arctic "solifluction."[43] Landsliding of a superficial nature is common also. Where such conditions prevail concave valley-sides and in general

[42] N. Krebs, *loc. cit.* (10), p. 79.

[43] K. Sapper, *Geomorphologie der feuchten Tropen*, pp. 12-79, 1935; F. W. Freise, *loc. cit.* (18).

the concave parts of the characteristic compound landscape profiles of maturity develop out of all proportion to summit convexities, so that these latter tend to disappear, leaving steep upper slopes, sharpened summits, and knife-edge divides (Fig. 33). As a result the reduced residuals in a late-mature landscape are very steep-sided; but these are "inselbergs" only in the sense of W. Penck.[44] They

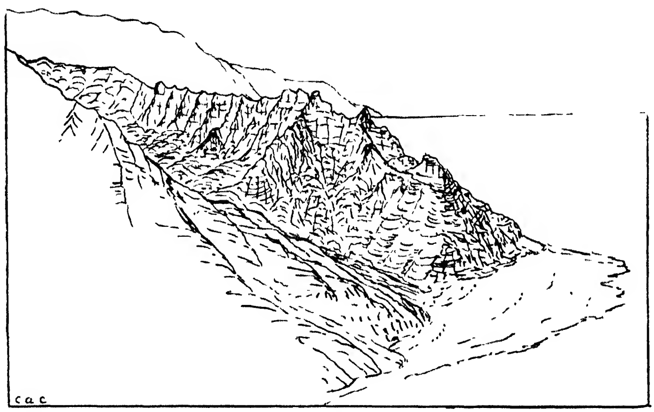

Fig. 33. Dissection in a hot, wet climate producing knife-edge divides. Windward side of Kauai, Hawaiian Islands (annual rainfall 100 inches). (Drawn from a photograph.)

may be distinguished from the residuals of a true "inselberg landscape," for around them the characteristic sharp basal nick of the latter is replaced by a sweeping concave profile.

Even this distinction may fail, however. In the valleys of large rivers that are either vigorously enlarging flood plains or rapidly building aggraded plains the concave lower slopes of valley sides will be either destroyed by undercutting due to lateral corrasion or buried beneath alluvium, and in either case a flat valley floor will then meet a steep valley side at a sharp angular intersection. This may be the case in the Orinoco landscape described by Passarge (p. 84).[45]

[44] *Loc. cit.* (11).
[45] K. Sapper, *loc. cit.* (33).

CHAPTER VIII

The Savana Cycle

It seems to be a safe assumption that the scarped forms of inselbergs are developed under conditions which do not favour soil formation or forest growth but promote dry weathering and encourage a back-wearing process. A mechanism must be available, however, for the removal of debris as it falls or slides down to the bases of slopes that are undergoing disintegration. On "inselberg landscapes," just as in arid pedimented regions, running water is without doubt the agent chiefly responsible for transportation of the rather fine debris which is produced by the slow activity of back-wearing processes.

The intermont plains are level and smooth enough in typical examples to be in the main broadly-cut confluent plains of lateral corrasion developed by rivers of low gradient which carry considerable volumes of water in the current cycle or, if the landscape is relict, have done so in a very recent pluvial climatic phase.

Various observers have been convinced that the foregoing conditions are fulfilled in most of the regions in which the "inselberg landscape" (in the properly restricted sense) has been recognised. They are characterised by an alternation of wet with rather long dry seasons in which high temperatures occur; so that vegetation is scanty except along water courses. This is the "savana climate."[1]

Relict Hypotheses

Before discussing erosion conditions in the savana climate some reference must be made to hypotheses of development of more or less similar inselbergs and plains under more arid conditions. There is, indeed, fairly general agreement that considerable changes of climate have recently occurred, especially in Africa,[2] these being in the main oscillations of climate resulting from rather wide

[1] See, for example, N. Krebs. Morphologische Beobachtungen in Südindien, *Sitz. Ber. Pr. Ak. Wiss.*, Ph-M. Kl. 23, p. 719, 1933.

[2] See, for example, E. J. Wayland, Desert versus Forest in Eastern Africa, *Geog. Jour.*, 86, pp. 329-341, 1940.

migration of the tropical high-pressure belt of aridity. Thus the discovery of some relict landscapes must be expected.

The Arid Aeolian Hypothesis

Though Passarge has more lately professed an open mind on the question of the origin of "inselberg landscapes,"[3] his name is generally associated still with the hypothesis of wind scour developing plains and isolating inselbergs, which he formulated in 1904.[4] His theory was later modified by the introduction of alternation of humid epochs, in which deep weathering has taken place, with epochs of desiccation, in which aeolian erosion has operated.[5]

Such theories have declined into disfavour, and it is the well-considered opinion of Blackwelder that "the topography of deserts to-day does not . . . . appear to reveal major features that have been produced directly by aeolian corrasion."[6] Evidence has been cited earlier (Chapter II), however, that deflation assists in the excavation of level-floored hollows, and the whole hypothesis of aeolian planation cannot be lightly discarded. There may be some inselbergs and plains of aeolian development; but it would be rash to assume such a general relict explanation of the landscapes of the savana belts, especially as the development of the inselberg-and-plains assemblage seems now to be in progress there under the existing conditions of climate.

In the most arid parts of the Kalahari Desert, the locality in which Passarge[7] distinguished the "Bechuana type" of inselberg landscape, "inselbergs" may perhaps have been isolated by deflation; and such may be the case also in some other regions of extreme and long-continued aridity such as Ahaggar, in the central Sahara, where the Quarternary pluvial epoch has been but a passing phase preceded as well as followed by aridity. Here (around a knot of mountains) "plane surfaces largely predominate," and "from the

[3] S. Passarge, *Panoramen afrikanischer Inselberglandschaften*, 1928; *Zeits. f. Geormorph.*, 4, 1929.

[4] S. Passarge, Die Inselberglandschaften in tropischen Afrika, *Naturwiss. Wochens.*, 3, pp. 657-665, 1904; Rumpffläche und Inselberge, *Zeits. deutsch. Geol. Gesells.*, 56 (Protokol), pp. 195-213, 1904; *Die Kalahari*, 1904.

[5] S. Passarge, Das Problem afrikanischer Inselberglandschaften, *Petermanns Mitteilungen*, 70, pp. 66-70, 117-120, 1924.

[6] E. Blackwelder, Yardangs, *Bull. Geol. Soc. Am.*, 45, p. 164, 1934.

[7] In 1904.

level surfaces the needles [inselbergs?] rise with startling abruptness; they appear to be set on the plains . . . . like bottles on a table."[8]

One must be prepared, however, to entertain the hypothesis that the major landscape features of even the most arid parts of the Kalahari and other deserts were originated by erosion that was partly fluvial in a semi-arid or perhaps savana climate prevailing in a past age and have suffered only slight modification under the present conditions of desiccation.

The Pedimentation Hypothesis

The representations of the landscapes of Adamawa and Northern Nigeria in the panoramas of Passarge[9] emphasise in every case the

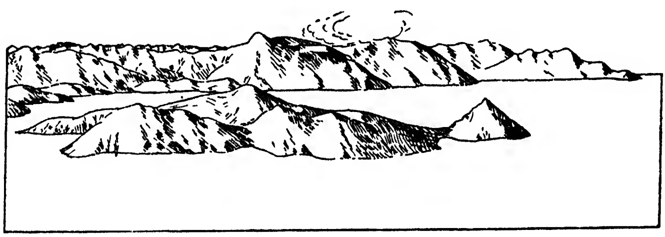

Fig. 34. Mature savana landscape at the western side of the Alantika Mountains Adamawa, W. Africa. (After Passarge.)

scarp-foot re-entering angles but do not reveal any details of the plains (Fig. 34). Consistently with this he describes the plains as flat and featureless except for the presence of a few shallow river channels. Though the insignificance of the slopes is "astonishing," it is clear that they slope with river gradients. On the Adamawa-Nigerian plains the gradients are insufficient to prevent extensive flooding, which is indeed a normal feature of the rainy season. Such flooding does not imply complete absence of slope but does indicate a general flatness of the surface and an incapacity of river channels to carry off the precipitation rapidly. There is, moreover, no record of the presence of any steeper slopes leading down from the bases of inselbergs to the levels of the flat surrounding plains. Instead of such a fringing "pediment" Passarge[10] records the rather

[8] E. F. Gautier, The Heart of the Sahara, *Geog. Rev.*, 16, pp. 378-394, 1926.
[9] *Loc. cit.* (3) (1928).
[10] *Loc. cit.* (3) (1928), p. 14 (*Bergfussniederung*).

common occurrence of a linear depression close to the base of the scarp.

In other parts of Africa landscapes which are included in the category of inselberg landscapes by Passarge and figured as such do not in reality conform to the type. These have much steeper slopes on the plains, the profiles of which indicate an origin as pediments fringing the hill or mountain residuals. Marno's illustrations (copied by Passarge[11]) of the landscapes of Kordofan and Gondokoro, which include pediments or bahadas or a combination of these, show distinctive piedmont slopes rather closely conforming to the mountainous-desert type.

Johnson[12] has found no difficulty in adopting such an explanation for some South African landscapes, and Wayland[13] also specifically refers in an account of the features of a semi-arid Central African plain to extensive "pediments", which he has described more fully as "gently-sloping rock platforms thinly covered with deposits." These fringe "very abrupt hills and mountains" and "separate them from the flats proper." In a lecture entitled "Face of Uganda" the same author has indicated the preponderance of this type by referring to "the ubiquitous pediments of the hills."[14]

The fact that pedimented landscapes of semi-arid origin are common in Africa and have been confused by some authors with the inselberg landscapes of the savana type must therefore be borne in mind. These must, however, be regarded as distinct from the true inselberg-and-plains or savana landscapes of the savana belts.

The Savana Landscape: Composite Planation Hypothesis

An attempt to apply the simple pedimentation hypothesis to the savana landscape meets with the difficulty that here typical piedmont slopes are absent. Narrow piedmont slopes such as have been termed miniature pediments[15] seem to be present, however, leading down to river channels, and published descriptions of the processes in operation suggest that inselberg scarps are worn back by weathering

[11] *Loc. cit.* (3) (1928).

[12] D. Johnson, Planes of Lateral Corrasion, *Science*, 73, 174-177, 1931.

[13] E. J. Wayland, Outlines of the Physiography of Karamoja, *Geol. Surv. Uganda Bull.*, 3, pp. 145-153, 1938.

[14] E. J. Wayland, *Abst. Proc. Geol. Soc. London*, 1348, p. 3, 1938.

[15] Douglas Johnson, Miniature Rock Fans and Pediments, *Science*, 76, p. 546, 1932; W. H. Bradley, Pediments and Pedestals in Miniature, *Jour. Geomorph.*, 3, pp. 244-255, 1940.

and miniature pedimentation, while the surrounding plains are extended by lateral river planation.

River channels, where shown at all, in Passarge's panoramic illustrations are more or less axial in the plains; but the occasional and very significant presence of *marginal* courses is mentioned by him in his text. He insists, indeed, on the importance of a shallow linear depression[16] which rather commonly separates the plains from the base of an inselberg scarp. Such depressions are clearly river channels, but some of them have been cut off or otherwise abandoned.

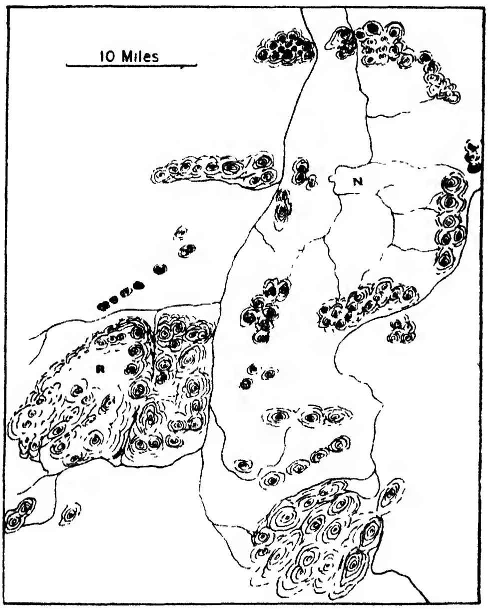

Fig. 35.
Plains and inselberg groups in an area including the Ribawe Range (R) and Nrassi Basin (N) in central Mozambique. (After Holmes and Wayland.)

A map by Holmes and Wayland[17] of part of the district of Mozambique also shows quite clearly that rivers there consistently hug the mountain bases in a manner that cannot be fortuitous (Fig. 35). Thus it may be accepted that the presence of channels closely following the base lines of larger inselbergs and residual mountain groups, and even partly encircling them, is a characteristic feature of the savana landscape.

[16] *Bergfussniederung.*
[17] A. Holmes, Rocks of the District of Mozambique, *Quart. Jour. Geol. Soc.*, 74, Pl. XI, 1919.

Thorbecke's[18] account of the savana landscape in Mbam (south of Adamawa), in West Africa, suggests a possible mode of development and enlargement of the plains.

The climate of Mbam is considerably wetter than the average for most districts with the typical savana landscape, and it has a somewhat shorter dry season. The dry season is very well marked, however, and is very sunny and hot. Vegetation is rather scanty. Landscape residuals of inselberg form, apparently in course of development under existing conditions, are remnants of a dissected granite plateau capped by a strong layer of laterite, so that they commonly assume mesa and butte forms bounded by escarpments somewhat like the breakaways of Western Australia, but higher. A scarp-foot depression is typically present, and is generally a watercourse.

Back-wearing of the scarps of the tabular upland remnants and the steep flanks of smaller buttes and of inselbergs that have become dome-shaped is progressing rapidly and is ascribed by Thorbecke largely to insolation which results in exfoliation in the hot dry season; but the scarps are attacked also by chemical weathering in the wet season. The granite debris falling to the foot of a scarp is rapidly reduced to a sandy texture and the sand is swept by sheetfloods in the wet season into rivers, which carry it away.

This reference to sheetflood transportation of sand indicates the presence of a miniature pediment sloping from the base of the scarp towards the bed of a stream that flows parallel to the line of the scarp and not far from it.

On the basis of Thorbecke's data a hypothesis may be outlined for the explanation of the development and extension of the intermont plains between and among inselbergs. As the scarp of a residual upland retreats the stream flowing parallel with the base of the scarp must migrate horizontally with it; for otherwise scarp-foot depressions and river channels would not remain common features of the landscape. The miniature pediment normally present fringing the base of the scarp will be progressively encroached upon by the river and forced back as the stream cuts laterally.

[18] F. Thorbecke, Der Formenschatz im periodisch trockenen Tropenklima mit überwiegender Regenzeit, *Düsseldorfer Geogr. Vortr.*, 3, 1927 (quoted extensively in K. Sapper, *Geomorphologie der feuchten Tropen*, pp. 104-107, 1935).

The question arises whether a river flowing parallel to the scarp will have any tendency to cut unilaterally towards it. The river will, without doubt, swing and cut both to its right and left; but on the side remote from the upland scarp vegetation will gain and maintain a footing on the margin of the river-bed, and the surface may thenceforth be built up there by accumulation of flood-borne silt and wind-borne sand and dust, which will be held by the vegetation. Stream swinging and migration away from the scarp is likely to be somewhat checked by such accumulated material, so that the stream will be forced over to some extent against the scarp. In Mbam the flood plains of the rivers have been built up by some such means to a height of about 30 feet above the river-beds, so that it appears that this is the depth of burial of the approximately horizontal surface that has been cut on the bedrock as a result of combined scarp back-wearing and river planation.

From Thorbecke's account of the plains of Mbam it seems justifiable to generalise that the plains of typical savana landscapes are in the main widely developed plains of lateral river planation. This points to a reasonably close analogy with stream-cut pediments in semi-arid New Mexico (Chapter III); but the gradients of the savana-landscape rivers are in general considerably gentler because of the large volumes of water they carry in the wet season, and commonly also because of the fine grade as well as moderate supply of the waste they carry away from a land surface which in most parts is of no great relief and is approaching planation.

At a late stage of the landscape cycle such low-gradient plains developed by adjacent rivers can become confluent by cutting laterally through divides, and parts of ridges and spurs that are separated from main ranges will thus become inselbergs in a manner that has been indicated by Johnson.[19] In this case, indeed, the accordance of levels at the points where adjacent river-cut plains become confluent is likely to be much closer than in the case of the steeper-gradient rivers of semi-arid mountain regions.

[19] D. Johnson, Rock Planes of Arid Regions, *Geog. Rev.*, 22, Fig. 1, p. 657, 1932.

Jessen's Hypothesis

An alternative hypothesis to account for the retreat first of scarped slopes bordering steep-walled young valleys in the youth of the savana cycle and eventually also those of upland residuals at a later stage has been advanced by Jessen[20] following studies of the landscape of Angola.

He postulates a retreat of valley walls and inselberg scarps without loss of their steepness and a resulting lateral extension of plains at or near river levels. The mechanism relied on to produce the recession of scarps without change of steepness is as follows: Under hot climatic conditions with alternating wet and dry seasons the foot of a scarp is in the zone of most intense chemical weathering, because rock debris accumulates there and so the soil contains moisture even in the dry season, whereas on upper slopes bare rock is exposed and is usually dry so that chemical weathering is at a minimum. Therefore, so the argument goes, denudation will proceed most actively along the foot of the scarp and as a result the whole scarp will be sapped back. Jessen would extend this hypothesis so as to explain Tertiary peneplanation in Europe as due to the prevalence of a savana climate.

Monolithic Inselbergs

It is reasonable to suppose that lateral river corrasion and, more especially, the process of back-wearing of scarps that precedes it will be slowest on rock bodies most resistant to weathering, whether these be composed of rock different in kind from their surroundings or owe their resistance to freedom from close jointing. So, at a certain stage of landscape development these more resistant and monolithic parts of the terrain will be found surviving in inselbergs. Thus may be explained an abundance of domed and sugarloaf forms among inselbergs in favourable terrains (Figs. 30, 36). Such geomorphic "monoliths," shaped to a great extent by large-scale exfoliation to form both isolated small inselbergs and the individual peaks of inselberg groups, are shown by published photographs to be common forms among the residuals of Northern Nigeria.[21]

[20] O. Jessen, Tertiärklima und Mittelgebirgsmorphologie, *Zeits. f. Erdk.*, pp. 36-49, 1938.

[21] J. D. Falconer, *Geology and Geography of Northern Nigeria*, 1911; A. D. N. Bain, The Origin of Inselbergs, *Geol. Mag.*, 60, pp. 97-101, 1923.

Holmes[22] describes them as common in Mozambique, and Hubert[23] records their presence in the extensive savana landscape around Wagadugu in the bend of the Niger.

This abundance of forms rounded by large-scale exfoliation differentiates the inselbergs of savana landscapes to some extent from the residuals left at the stage of incomplete pedimentation

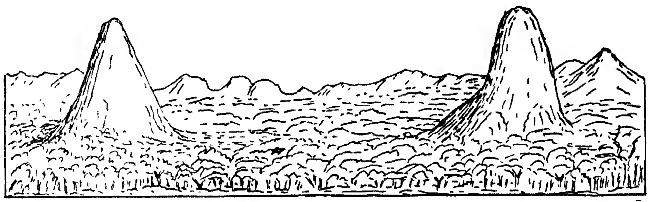

Fig. 36. Sugarloaves of the Ribawe inselberg group, Mozambique. (Outlined from a sketch by E. J. Wayland.)

in extratropical deserts. In the latter case the weathering of retreating scarps, whether it be mainly physical or chemical, has been observed to break up granite first into large boulders (Pl. VII, 1) and later into coarse sand. Large-scale exfoliation, which shapes monoliths into sugarloaves and domes, is more likely to occur where there is a wet season, which will promote hydration and similar chemical processes liable to cause expansion and separation of thick shells of rock.[24]

In the case of gneissic inselbergs in Mozambique a peculiar relation of the landscape form to the structure of the gneiss has been observed; it is as though long continuance of a process of exfoliation controlled in some way by the gneissic banding has

22 *Loc. cit.* (17).

23 H. Hubert, *Mission Scientifique au Dahomey,* p. 121, Paris, 1908.

24 E. Blackwelder, Exfoliation as a Phase of Rock Weathering, *Jour. Geol.,* 33, pp. 793-806, 1925. Another cause of exfoliation which has been suggested, and which must not be entirely overlooked, is expansion owing to relief of pressure as a result of the erosion which has led to exposure of the rock at the surface. (G. K. Gilbert, Domes . . . of the High Sierra, *Bull. Geol. Soc. Am.,* 15, pp. 29-36, 1904.) R. Farmin (Hypogene Exfoliation in Rock Masses, *Jour. Geol.,* 45, pp. 625-635, 1937) is convinced that this is the prime cause of all exfoliation. It is perhaps excusable to draw attention to the incompatibility of this theory with Willis's theory (p. 80) that monolithic domes have survived since the Palaeozoic era without suffering any appreciable erosion. Such comparison of the two theories does not commit one to support either of them.

eventually brought the shapes of the domes to conform with the dips and folds of the foliation until "the strike swings round the contours of the hills and the foliation dips away from their summits in every direction, occasionally even to the extent of being practically coincident with the actual surface."[25] Such coincidence is not invariably found, however. Neither is it peculiar to the savana-climate domes; for it has been observed on monoliths in Canada.

It must be emphasised that the mere survival of geomorphic monoliths which assume dome or sugarloaf forms, notwithstanding their common occurrence among the forms taken by inselbergs and the component parts of inselberg groups consisting of granite-gneissic rocks, does not bring the landscape in which they occur into the category of "inselberg landscapes." Such forms occur very abundantly in the hot rain forest region of eastern Brazil,[26] and make their appearance also on favourable terrains in all parts of the humid temperate zones as variants of the "normal" landscape.[27]

A Generalised Savana-landscape Profile

This sketch of the savana cycle may be concluded with a brief comparison of a possible succession of landscape forms in this cycle with those of (*a*) the arid cycle (with emphasis on deflation) and (*b*) the pedimentation cycle under arid to semi-arid conditions, where each is introduced by the more or less uniform upheaval of a peneplain or other thoroughly denuded surface of former erosion. To the generalised deduced profiles of these three (in Fig. 37) another is added suggesting fully mature normal dissection in a hot, humid climate (p. 89). .

(*a*) *Arid Conditions*: Wind-excavated (P'ang Kiang) hollows or dry-lake floors bordered by breakaways will be excavated and will be bordered by pediment strips or miniature pediments leading down to nearly level rock floors. Extension of the hollows will reduce the area of residual level upland. A stable—that is, long enduring—stage will be characterised by the presence of mesa-like residuals, and a stage with coalescing pediments may follow; but

[25] A. Holmes, *loc. cit.* (17), p. 34.

[26] F. W. Freise, Inselberge . . . Brasiliens, *Zeits. Geomorph.*, 10, pp. 137-168, 1938.

[27] R. W. Chapman, Monoliths in the White Mountains of New Hampshire, *Jour. Geomorph.*, 3, pp. 302-310, 1940.

the processes may repeat themselves, and two-storied or multi-storied (stepped) rock floors may be found.

(*b*) *Semi-arid Conditions*: Quasi-normal and, it may be, deep dissection will occur in the youth of the cycle, accompanied and followed by much lateral planation by streams with somewhat steep

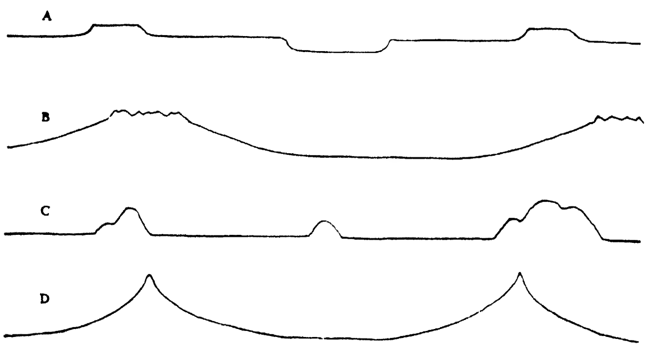

Fig. 37. Deduced characteristic profiles of maturity in (A) arid, (B) semi-arid, (C) savana, and (D) hot-humid cycles of erosion.

gradients. Residuals between the plains so formed will dwindle in both area and relief and will be reduced to nubbins by scarp-retreat and pedimentation. With destruction of residuals a stage characterised by steep coalescing pediments will supervene—a peneplain of semi-arid erosion, still retaining broad undulating relief.

(*c*) *Savana-climate Conditions*: Early quasi-normal dissection will be accompanied and followed by extensive development of plains of lateral river planation with decidedly lower gradients than those prevalent in case (*b*). The upland will be reduced to steep-sided inselbergs with only miniature pediment fringes and these inselbergs will still tower imposingly above the widespread surrounding plains.

CHAPTER IX

Sand Dunes and other Aeolian Deposits

VAST areas in the Sahara and Arabian deserts, though not a large proportion of the whole region, are covered by undulating seas of drifting sand. These sandy (as contrasted with stony) deserts are termed "ergs" in Algeria and the name has been given a general application (Pl. VIII, 1). The ergs of the Libyan Desert trail far south-eastward (to leeward)[1] from oasis-containing hollows which have presumably been excavated, or at least greatly enlarged, by deflation, as has been assumed by Walther,[2] Hobbs,[3] and Ball.[4]

The ergs of the Sahara region are contained within the boundaries of broad and shallow basins. Smaller ergs are found also in basins of tectonic origin forming part of mountainous deserts. The sand of which they are built has been blown from dried-up lake-floor deposits in the axial playas towards which waste is carried occasionally by ephemeral streams. In some cases it consists of broken crystals of gypsum which has been precipitated in the playa muds. These small ergs huddle to leeward of the playas (Pl. VIII, 1).

The desert sand is subject to abrasion as it is drifted and redistributed by the winds, and the milling process produces some of the dust which wind ultimately exports from the region. By no means all the sand is thus destroyed, however, and it is possible for a great thickness of blown sand to accumulate where the local base-level is rising. This may be either in one of the closed basins of a mountainous desert, into which detritus is constantly being swept, or it may be on a subsiding land surface. Vast quantities of desert sands that have accumulated in long past geological periods have been indurated to form sandstone rocks. Induration of

[1] S. Passarge (Geomorphologische Probleme aus Algerien, *Jour. Geomorph.*, 3, pp. 116, 127, 1940) claims, however, that the direction of sand drift both in the Sahara and Kalahari deserts is not in the direction of prevailing winds but in each case northward, in which direction the sand is carried by occasional gales from the south.

[2] J. Walther, *Das Gesetz der Wüstenbildung,* 1900.

[3] W. H. Hobbs, The Erosional and Degradational Processes of Deserts with Especial Reference to the Origin of Desert Depressions, *Ann. Ass. Am. Geog.*, 7, pp. 25-60, 1917.

[4] J. Ball, Problems of the Libyan Desert, *Geog. Jour.*, 70, 1927.

calcareous sands, which are built into dunes on shores bordering warm seas and are composed largely of foraminiferal shells and of the comminuted shells and skeletons of larger calcareous organisms, takes place very rapidly, and the forms and internal structures of calcareous dunes and dune ridges are preserved by the conversion of the calcareous sand into limestone.

In addition to desert ergs there are very extensive sand-covered areas in coastal districts in most parts of the world and under various climates (including humid); the sand in these is derived from the littoral marine detritus and calcareous organic debris which dries on beaches and is blown inland. Sand is derived in a similar way from the broad beds of braided rivers and, especially in semi-arid regions, from the sandy alluvium of river deposits on valley floors and also those left on terraces. Rarely in such cases does the sand accumulate so rapidly as to prevent entirely the growth of vegetation. Where the supply of sand is somewhat restricted, under both semi-arid and humid conditions of climate sand-binding plants fix the surface either throughout the dune area or in patches, resulting in the latter case in the production of ragged landforms due to partial fixation and contemporaneous deflation of the surface. These bear little resemblance to the more symmetrical streamlined constructional hills of desert sand.

Sand Drifts and Dunes

In general sand transported or in course of transportation by wind covers the bedrock surface either as a thin smooth sheet ("sand drift"[5]) or as a thicker layer the surface of which is accidented by hillocks, hills, and ridges termed collectively "dunes." A sand drift covering a landscape changes its form very little. Drifted sand may ascend hill slopes and even not too precipitous cliffs to great heights to build "cliff dunes."[6] On the west coast of northern New Zealand much sand is drifted inland over a hilly landscape which it covers both as thin drifts and as thicker wandering dunes (Pl. VIII, 2).

[5] "Sand drift": L. Cockayne, Dune Areas of New Zealand, *N.Z. Parl. Paper*, C-13, p. 14, 1911; C. A. Cotton, *Geomorphology of New Zealand: Part I, Systematic*, p. 261, 1922. R. A. Bagnold (A Further Journey through the Libyan Desert, *Geog. Jour.*, 82, p. 121, 1933) has attempted to appropriate this term for what he calls also "sand shadows." These are streamlined tails to leeward of projecting rocks.

[6] Such ascent of sand over cliffs 700 feet high is recorded by Cockayne (*loc. cit.* [5], p. 16).

Sand travels always close to the ground, moving forward in short leaps and contrasting thus with dust. If the supply of sand from desert, beach, or river-bed is kept up, a large area is overspread, though perhaps by only a thin drift. If the supply fails a sand drift quickly passes on and, as all vegetation has been killed by temporary burial, gullying of the re-exposed landscape by rain-wash may result in some badland development, or the finer constituents of the soil may be removed by wind so as to leave an infertile lag gravel in the trail of the sand drift.

Barchans

Instead of a continuous drift sheet there may be discontinuous hillocks if the supply has been intermittent, or perhaps a narrow elongate ridge of sand has been broken up by a cross wind, and

Fig. 38. Barchans in southern Peru. (From a photograph.)

such hillocks may travel across the land surface as isolated dunes. Isolated migrating dunes assume crescentic forms and are then termed "barchans"[7] (Pl. IX, 1; and Fig. 38). This form results from the tendency of the high central part of a heap to lag, while its margins, being lower and more readily moved forward, advance as horns pointing in the direction in which they are carried by the wind.

Sandfall Fore-set Bedding

Barchans and dunes in general have steep slopes on the lee sides (Pl. IX, 1 and 2). Such a slope may be as steep as 33°, the angle of repose for sand (according to Bagnold), in which case it has been termed a "sandfall" by Cockayne (Pl. IX, 2). Having been driven over the sharp crest of the dune by the wind, the sand slides down and comes to rest in the wind shadow to leeward.[8]

[7] J. Walther, *loc. cit.* (2).
[8] A sandfall slope is termed by Bagnold a "collapsing front" (*loc. cit.* (5), p. 121).

Windward slopes, which the sand ascends, are variable, but generally quite gentle, a slope of 4° being common; and where great bodies of sand are advancing across country as "wandering dunes" they may have broad horizontal summits, or the summits and gentle windward slopes may be diversified by secondary transverse dunes forming minor undulations.[9] Some wandering dunes in New Zealand, covering areas up to five square miles, probably contain less sand than at first appears, as they bury hills of solid rock and are so thin in places as to be little more than drifts.[10] A broad dune expanse of this kind continues to grow in area as its front advances if the supply of sand is kept up. It is recorded that the advance of one such steep dune front, or sandfall, in New Zealand took place at the rate of nine feet per year over a period of 44 years.[11]

As forward growth takes place as a result of the tipping of successive loads of sand over the crest by successive gales, the sand coming thus to rest builds forward a succession of layers each with the inclination of the sandfall. Finer and coarser layers deposited by alternating breezes and gales may be distinguished if the sand is naturally or artificially trenched so as to reveal the structure. By analogy with delta structure this construction is often referred to as "fore-set" bedding. Where ancient coastal or desert dunes have been converted into hard rocks they commonly display such aeolian inclined, fore-set, or "cross" bedding, somewhat resembling in this respect the structures of small and irregular deltas and the cross bedding developed on a smaller scale and with less steep inclination by the deposition of gravelly sands in current-stirred shallow waters.

If a dune, in a region of variable winds, has sandfall fronts facing in various directions, the inclination of the fore-set cross bedding correspondingly changes from place to place; and where, owing to aeolian aggradation dunes are built over earlier dunes or over the deflated stumps of earlier dunes the inclined beds of successive sand deposits may dip in various directions. Besides the fore-set arrangement other types of irregular bedding develop under the conditions of accumulation described on page 107.

[9] J. A. Steers, The Culbin Sands and Burghead Bay, *Geog. Jour.*, 90, pp. 498-528, 1937.

[10] L. Cockayne, *loc. cit.* [5], p. 16.

[11] L. Cockayne, *loc. cit.* [5], p. 14.

Growth and Height of Dunes

Without attempting to explain why dunes are formed instead of smooth drifts or to relate the larger forms of dunes to the tiny ripples on a sand surface which may be seen advancing with axes elongated at right angles to the wind,[12] one may note that obstacles such as bushes collect sand as mounds and that these may perhaps grow into dunes by collecting more and more sand in the eddy to leeward of the crest. It has been observed in some cases, however, that wind eddies caused by obstructions lead instead to the destruction of dunes by deflation.[13]

Coastal dunes commonly attain heights of 20 to 50 feet, more rarely 100, and occasionally even hundreds of feet. "There appears to be no upper limit to the size of a dune" (Bagnold). In the case of barchans and some migrating ridge forms the height is controlled by the limitation of supply of sand. A dune cut off from the source of sand is stripped progressively on the windward slope, and the sand so derived is swept over the crest and dropped by the wind on the sandfall. Thus the isolated dune or ridge advances; it consists entirely of fore-set beds, which are truncated by its windward slope.

Transverse Dune Ridges

Elongated dunes, forming ridges, develop both transversely to and parallel with the prevailing wind direction. Strong winds have been credited with the building of longitudinal and weaker winds of transverse dune ridges,[14] but very long longitudinal ridges in North Africa and Australia trend parallel to prevailing winds of moderate strength, while occasional strong winds blow across them (p. 113).

On extensive areas of deep loose sand—such as are produced by destruction of vegetation over formerly fixed dunes—numerous closely-spaced transverse dunes are formed in a pattern not unlike that assumed on a very much smaller scale by the familiar "ripple mark" on a sand surface. Such transverse embryonic dunes may

[12] According to Bagnold ripples never develop into dunes (*loc. cit.* [5]); see also R. A. Bagnold, *The Physics of Blown Sand and Desert Dunes,* 1941.

[13] J. Ball, Problems of the Libyan Desert, *Geog. Jour.,* 70, p. 215, 1927.

[14] V. Cornish, On the Formation of Sand Dunes, *Geog. Jour.,* 9, pp. 278-309, 1897.

grow from flattish mounds into higher dunes with characteristically steep sandfall slopes separated by sharp crests from gentler slopes to windward. Such patterned transverse dunes (and barchans also) are unknown in the condition of fixed, or "anchored," dunes.[15]

Long transverse dunes advancing with the wind assume the appearance of rows of coalescing barchans,[16] and their crests exhibit a complex of crescentic forms (Pl. VIII, 1) as the result of more rapid advance of the lower parts of ridge crests and the lagging of intermediate peaks, each of which then appears to advance like an individual barchan.

Further complications of the pattern are introduced by changing winds; and if strong winds blow frequently from various quarters traces of the intersection of two or more transverse dune systems may be found producing a patterned but not very regular spacing of peaks and hollows, and crescentic barchan-like crests will face in the direction of sand migration due to the various winds.

Foredune Ridges

The accumulation of coastal dunes may take place as ridges parallel to the shoreline. Such ridges are transverse to the wind from the sea, but originate quite differently from the ripple-like dunes already mentioned. They are classed by Melton[17] with "source-bordering lee dunes," a name which explains itself. The "source" is sand thrown up by waves on the adjacent beach, and the presence of dunes implies an abundant supply of such sand. If the shoreline is not advancing seaward (emerging or prograding) one ridge, or "foredune,"[18] may develop and grow to a great breadth, becoming in reality a belt of dunes, as sand is drifted landward across it and as it is progressively fixed by growth of vegetation. A typical enlarged foredune of this kind in Southern California (figured by Melton[19]) is bordered by long tongue-like extensions

[15] F. A. Melton, A Tentative Classification of Sand Dunes, *Jour. Geol.*, 48, pp. 113-145, 1940.

[16] E. de Martonne doubts whether extensive dune chains ever develop from coalescing barchans, as suggested by Walther; (E. de Martonne, *Traité de géographie physique*, 2, p. 957, 1935). Melton (*loc. cit.* (18)) points out that isolated dune ridges may break up into rows of barchans.

[17] *Loc. cit.* (15).

[18] German: *Vordüne.*

[19] *Loc. cit.* (15).

which are "longitudinal" ridges in the sense of being built parallel to the wind direction, and it is obvious that broad foredune belts grow mainly by agglomeration of such tongues. The New Zealand dune ridge figured in Plate X, 1, which originated as a foredune but is now inland owing to progradation of the shore, is fringed on the lee (landward) side by short tongues of this kind.

Up-growth in Dune Belts

Where vegetation binds and holds sand (whether it be derived from a sea beach or an inland source) upward growth of the features of a dune belt takes places as well as lateral extension, as has been shown by study of the bedding in areas of old, partly destroyed dunes. Growth may take place

> by the addition of fore-set, top-set, or back-set beds or by combinations of these, depending on the equilibrium between the rate of plant growth and the rate of burial by sand. Steep fore-set beds develop only when sand is swept in more rapidly than plant growth can keep pace, hence . . . . to be carried over the crest of the dune and deposited on the leeward side at the angle of repose. . . . Back-set bedding, the common type [in Kansas dunes], is developed when plant growth keeps ahead of the influx of sand, thus to trap the sand and cause it to bank up layer upon layer [compare back-set delta bedding, Chapter XXIV], on the windward side. This type of bedding has a low angle of dip and involves retrogressive growth of the dune. . . . Top-set beds may be laid down over either of the other types, differing only in their position at the top of the dune and in their essentially flat dip. . . . The original dunes grew upward and backward by accretion, under the continuous influence of vegetation, and were fixed in position from the beginning.[20]

Coastal Dune Belts and Ridges

Dune belts of such composite origin fringe many coastal lowlands. They may perhaps be classed as broad foredunes of complex form. On the southern coast of south-eastern Australia, for example,

[20] H. T. U. Smith, Geologic Studies in South-western Kansas, *Bull. Univ. Kansas*, 34, p. 160, 1940. Windward growth unassisted by plant protection has been observed in experiments carried out by R. A. Bagnold (The Transport of Sand by Wind, *Geog. Jour.*, 89, pp. 409-438, 1937).

an undissected low-lying coastal plain is striped with successively built belts of indurated calcareous dunes which mark successive shorelines during slow emergence of the coastal plain.[21] Spread over a zone 50 miles wide (Fig. 39) the dune belts, from a mile

Fig. 39. Belts of indurated dunes marking former shorelines on the undissected coastal plain of the south-eastern corner of South Australia.

to several miles across, are separated by generally wider, flat inter-dune strips.

On a prograding shore also a foredune may be deprived of its supply of sand before it has grown to large dimensions by the initiation of a new ridge to seaward of it. Successively built new beaches are bordered by successive new foredunes, and the earlier built ridges if fixed, or "anchored," by vegetation remain in parallel arrangement.

This has been the mode of accumulation of most of the sand in the dune-covered coastal forelands of the North Island of New Zealand, where vast supplies of sand derived from pumice eruptions

[21] L. K. Ward, The Underground Water of the South-eastern Part of South Australia, *Geol. Surv. S. Austr. Bull.*, 19, pp. 8-12 and Fig. 1, 1941.

in the centre of the island have been carried to the sea by west-coast rivers, leading to progradation of the shore.

In some parts of these dune areas, however, long longitudinal landwardly-directed tongues have developed also, the growth of which may perhaps be explained as similar to that of some elongated (and tapering) longitudinal dunes termed by Melton[22] "wind-shadow lee dunes" which are aligned in the lee of projecting rock masses or of the interfluves of a gullied landscape. The longitudinal dunes in the New Zealand coastal dune areas began their growth perhaps as tongues extending landward from the foredune, and longitudinal extension might continue as a sand shadow down-wind from that portion of the tongue already fixed by vegetation. They encroach on plains of deltaic origin (on the Manawatu delta, in western Wellington, for example), strips of which separate parallel dune ridges. These strips are swampy and have probably never been dry enough to serve as corridors through which sand could travel to be afterwards swept laterally on to the sand ridges (p. 113).

Blowout Dune Forms

Even on coastal dune belts and other sand accumulations in humid climates, where sand-binding plants flourish, ridges rarely retain their initial forms, especially if they have been built transverse to the wind. Imperfect fixation by vegetation or the local destruction of anchoring vegetation by over-supply of sand results in the cutting of wind-scoured gaps and hollows ("blowouts"), which break up dune ridges into a chaotic jumble of disconnected hillocks (Pl. X, 2)[23]. At the same time constructional hillocks of irregular form also grow up around clumps of rapid-growing sand-binders and contribute to the irregularity of the relief. In New Zealand "isolated mounds, generally formed by *Scirpus frondosus,* are common on sand plains and also on a wide seashore, where . . . . they may eventually build isolated hills or dune chains."[24]

Anywhere among the ridges and hummocks an extensive blowout may become a local source of sand from which begins the

[22] *Loc. cit.* (15). Termed by Bagnold "sand shadows" (*loc. cit.* (5), p. 121).

[23] "Under natural conditions the readvance of vegetation, being irregular in time and place, permits blowouts to form during the process of advance on those sand surfaces not yet anchored. This destroys the form so typical of bare-sand surfaces and leaves merely the pitted blowout surface" (Melton, *loc. cit.* (15), p. 135).

[24] L. Cockayne, *loc. cit.* (5), p. 15.

growth of a sand ridge longitudinally down the wind (a "source-bordering lee dune"). Such ridges may extend landward far beyond the dune strip initially built along a sea margin, encroaching on plains of deltaic origin or on the floors of filled-in lagoons in the manner already suggested (p. 109).

Somewhat similar longitudinal ridge-building may take place to leeward of a small local blowout, but if the sand supply from this source is limited in amount a spoon-shaped blowout hollow remains with a low crescentic dune ridge fringing it on the lee side. This is the "blowout" or "parabolic" dune of Melton's classification.[25] Melton's "windrift" dune is like the foregoing but is more elongated to leeward and can be formed only where the wind blows in a constant direction. "Many are a mile or more in length, though the width is only a few hundred feet. The sand rim is of a hairpin . . . . shape—opening towards the wind" (MELTON).

A SAND-DUNE CYCLE

Smith's[26] sand-dune cycle comprises two stages: (*a*) "Aeolian" (active stage) and (*b*) "Eluvial" (passive phase). These are characterised (*a*) by growth of dunes and (*b*) by a generally longer-enduring condition of protection of the surface by vegetation, accompanied by some gradual wastage and modification of form resulting from weathering and creep. The latter stage is subject at any time to "interruption through rejuvenation, whereby wind action is resumed and a new cycle inaugurated" (SMITH).

THE DUNE COMPLEX

The various types of ridges and chaotic assemblages of mounds found among anchored dunes, especially those of a coastal dune belt, are features of a "dune complex,"[27] which is diversified also in a well-watered region by the courses of such streams as must cross it to reach the sea, as is the case in the dune complex of western

[25] *Loc. cit.* (15). This explanation of parabolic dunes has been offered also by J. A. Steers (*loc. cit.* (9)). Some European "parabolic" dunes are explained by de Martonne (*loc. cit.* (16), p. 954) as a result of unequal retardation of the migration of transverse dunes by partial fixation. J. T. Hack recognises "parabolic" dunes both "of accumulation" and "of deflation" (Dunes of the Western Navajo Country, *Geog. Rev.*, 31, pp. 240-263, 1941).

[26] H. T. U. Smith, Sand-dune Cycle in Western Kansas, *Bull. Geol. Soc. Am.*, 50, pp. 1934-5, 1939; *loc. cit.* (20), pp. 159-64. Not the secular desert-dune cycle deduced by L. Aufrère, *Ann. de Géog.*, 40, pp. 362-385, 1931.

[27] H. C. Cowles, Sand Dunes of Lake Michigan, *Bot. Gaz.*, 26, p. 194, 1899.

Wellington, New Zealand. Blocked in places by wandering dunes (Pl. IX, 2) the smaller of such streams form lakes, shallow but in some cases of considerable extent. These, however, may later become choked with vegetation and converted into swamps. Larger rivers, on the other hand, maintain channels through the dune complex if capable of transporting all the sand tipped into them down the sandfall slopes of encroaching dunes.

Among inland dunes, especially in a rather dry region, an extensive blowout results in either exposing a "wind-scoured pavement" of bedrock or in producing a "wind-scoured hollow."[28] In a coastal dune belt, however, the ground water is generally close to the surface, and rather extensive flats, termed "sand plains" by Cockayne,[29] are developed by deflation at places where the sand is blown out down to the ground-water level; for, when this is approached and the sand becomes moist, "all further erosion ceases as by magic."[30] This may occur where dunes have been formerly fixed by vegetation but where local destruction of the plant cover by burial has allowed dry sand to be exposed over an expanding area to the attack of the wind.

Similar exposure of loose sand has allowed of the complete destruction of the relief of considerable parts of former dune landscapes, followed perhaps by rebuilding of dunes in a new "cycle."

When fixed by a cover of vegetation, which eventually holds in place a thin soil, the dune-complex landscape has a surface of small relief but with many steep slopes. These soil-mantled slopes become smooth and symmetrical, with a compound (convex-and-concave) profile as blowout and constructional slopes become modified by soil creep.

The dune complex comprises also many undrained hollows, from which water soaks underground, and it is generally quite without organised valley systems of its own, though it may be traversed by the courses of the occasional through-going rivers such as are extended across a coastal foreland. In an inland dune complex, however, the level of ground water may be deep enough to cause all inflowing streams to be swallowed by the sand.[31]

[28] H. T. U. Smith, *loc. cit.* (20).
[29] *Loc. cit.* (5), p. 14.
[30] L. Cockayne, *loc. cit.* (5).
[31] H. T. U. Smith, *loc. cit.* (20), p. 154.

As the surface is scarcely affected as yet by water erosion, it may be described as infantile in the geomorphic cycle. As there is practically no run-off from individual dunes, dissection by streams is long delayed; but the loose sand composing even non-calcareous dunes becomes compacted, partly weathered, and less permeable as time goes on, and when run-off becomes possible the landscape may be subject eventually to denudation and peneplanation.[32]

Changes in the character of aeolian soils which proceed in the course of a normal cycle on a surface which was initially a dune landscape are thus described by Coffey and Rice[33]:

> When the sandhills become stationary, weathering immediately begins to work changes in the character of the soil. A large proportion of the sand grains are feldspar and minerals other than quartz, and they break down readily and undergo chemical changes with comparative rapidity when exposed to weathering. While the original material varies in composition, the dune-shaped hills, which are now stationary, must owe their present loamy character to the decomposition of the sands once loose and incoherent. In some localities the hills have long been stationary, and the dune-like contours have been modified by weathering and erosion.

Desert Dune Belts and Sand Ridges

A typical extensive desert erg may be a chaotic wilderness of irregularly wandering dunes (resembling those shown in Pl. VIII, 1) apparently without system; but these are generally collected into somewhat irregular longitudinal "ridges" or dune-covered strips. In the sandy regions of the Algerian Sahara and in parts of the Libyan Desert these dune belts are aligned with the prevailing winds.[34] Far from being symmetrical smooth ridges most of the Saharan belts present rather confused patterns of dune crests. The

[32] For a landscape of subdued and small relief in Washington County, Colorado, which is without any traces of integrated drainage, but is pitted instead by very numerous water-holding hollows, the description "an old-age dune topography" has been chosen by H. T. U. Smith (Aerial Photographs in Geomorphic Studies, *Jour. Geomorph.*, 4, pp. 171-205, *especially* Fig. 6, 1941) as the more probable of two suggested explanations. If these landforms are correctly explained as of aeolian origin, however, the landscape of which they form a part is still very far from old age in the geomorphic cycle.

[33] Quoted by H. T. U. Smith, *loc. cit.* (20), p. 162.

[34] E. de Martonne, *loc. cit.* (16), p. 958; J. Ball, *loc. cit.* (4), p. 215.

dune-covered strips are from a mile to several miles wide (as shown on published topographic maps),[35] and the intervening strips, which are for the most part quite bare of sand, are as wide and in some places considerably wider. Wind apparently sweeps these corridors clear of sand, which is driven laterally into the dune-covered strips. "The boundary between the dune and the ground on which it lies is very distinct. The sand gives the impression of having been swept up into the dune heap with a broom."[36]

For the collection of sand into dune belts and sand ridges a "shepherding effect of winds a point or two off the normal" has been appealed to[37]; and another suggestion is the attraction of electrically charged sand grains by dunes.[38] Bagnold[39] finds a satisfactory explanation in the occurrence of a prevailing wind of moderate strength in the longitudinal direction with less frequent transverse gales as well. The prevailing wind brings sand from the source and spreads it as thin drifts held among the pebbles on the stony-surfaced strips between the ridges. Strong transverse winds, which blow occasionally, clean this sand up and add it to the ridges. It has been suggested, but not proved, in Australia that sand has been derived by aeolian abrasion from gibber plains between sand ridges, and that some of the relief of the ridges is due to a lowering of the inter-dune strips by this process.

In the "Sand Sea" of the Libyan Desert, which covers many thousands of square miles, there are very numerous longitudinal ridges composed of *seif* dunes (Bagnold), some of which exceed 300 feet in height; some ridges are 60 miles long. Some long, smooth, and regular ridges of lower and broader form have been termed "whalebacks."[40] All trend south-south-eastward.

In the arid central region of Australia a moderate supply of sand is distributed widely over extensive plains as very numerous low sand ridges, narrow, straight, and of regular form elongated in the direction of prevailing winds. The collection of the sand into

[35] See examples of such maps in E. de Martonne, *loc. cit.* (16), pp. 959, 960.
[36] R. A. Bagnold, *loc. cit.* (5), p. 122.
[37] H. King, Study of a Dune Belt—discussion, *Geog. Jour.*, 51, p. 252, 1918.
[38] J. Ball, Problems of the Libyan Desert, *Geog. Jour.*, 70, p. 217, 1927.
[39] R. A. Bagnold, The Transport of Sand by Wind, *Geog. Jour.*, 89, pp. 409-438, 1937.
[40] R. A. Bagnold, *loc. cit.* (5).

steep-sided ridges separated by bare ground is here clearly a result of the influence of transverse winds, which may cause also some slow lateral migration of the ridges, for this wind direction is indicated by asymmetry of ridge profile, the steeper side being obviously a sandfall (Fig. 40).

The largest area covered by sand ridges in central Australia is the Simpson Desert, north of Lake Eyre.[41] A smaller relict, but otherwise typical example has been described in the Mallee district of Victoria.[42]

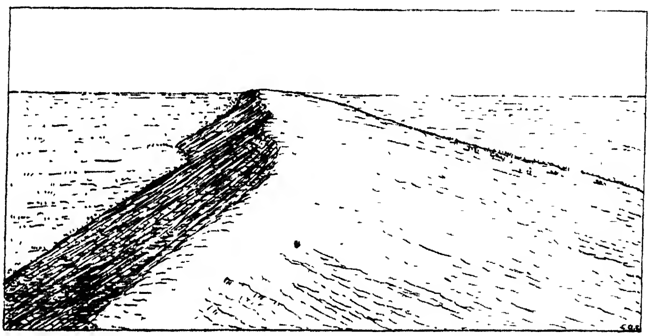

Fig. 40. Profile of an even-crested sand ridge in the Simpson Desert, showing the eastward sandfall slope. (After a photograph by Madigan.)

In both these areas the ridges are parallel to the prevailing wind direction, which is south-south-east in the Simpson Desert and west in Victoria. In both also the same distinct asymmetry of ridge profile is present (Fig. 40) and, as this takes the form of steepening on the eastern sides of the Simpson Desert ridges and on the south sides of the Mallee ridges, it is regarded as an effect produced by important secondary (but sometimes strong) winds from the west and north respectively.

[41] C. T. Madigan, The Australian Sand-ridge Deserts, *Geog. Rev.*, 26, pp. 205-227, 1936; The Simpson Desert and its Borders, *Jour. and Proc. Roy. Soc. N.S.W.*, 81, pp. 503-535, 1938; see also F. W. Whitehouse, The Surface of Western Queensland, *Proc. Roy. Soc.* Queensland, 53, pp. 1-22, 1941.

[42] E. S. Hills, The Physiography of North-western Victoria, *Proc. Roy. Soc. Vic.*, 51, pp. 297-323, 1939.

The Great Sandy Desert and Great Victoria Desert, in Western Australia, are similar in a general way to the Simpson Desert; but in these the prevailing winds, parallel to which the sand ridges are aligned, are more easterly.[42a]

The Mallee ridges contain internal evidence that they have long been features of the landscape, having been built up extremely gradually during certain climatic epochs when there has been a supply of sand available, and never migrating far laterally. Their dimensions and pattern are similar to those of the active Simpson Desert ridges, which will be described.

As defined by Madigan, the Simpson Desert is a plain of almost regional extent, having an area of 56,000 square miles. The sand ridges which diversify its surface are only 30 to 100 feet high, with 40 feet as an average figure, and are a quarter of a mile apart. They control all other phenomena of the desert surface, such as the courses of ephemeral streams and the elongation of small local areas of centripetal drainage ("clay pans"). The ridges

> are narrow and remarkably straight, and run continuously for at least 100 miles in places . . . . The north-east side is universally the steeper. . . . They are fixed by vegetation, ... the only signs of movement being along their length. The north-west ends can be seen to be extending in small aprons of loose sand, while the south-east ends show signs of ablation. . . . In occupied country . . . . the general movement of the sand is well known to be along the length of the ridges and in a north-north-west direction. The crests of the ridges are always composed of loose sand. . . . Winds [other than the prevailing wind] make minor crescentic dunes on top of the ridges that change their form with changing winds. . . .
>
> There are no barchans. . . . There are never any lines of sand running out at an angle to ridges. Ridges occasionally coalesce in a tuning-fork arrangement, when the stem of the fork is always to the north-north-west. The inter-ridge areas are sometimes swept clear of sand. . . . Sometimes over wide areas the inter-ridge spaces are also covered with sand, as in the central parts of the desert. . . . They merge into a sandy

[42a] C. T. Madigan, *loc. cit.* (41) (1936).

> plain with increasing vegetation in the north. . . . The sand is a fine quartz sand of a striking red colour.[43]

In the Libyan Desert a breaking-up into barchans at the lee ends of longitudinal ridges has been described by Bagnold.[44]

In the less intensely arid parts of the Australian interior many isolated dunes and patches of dunes occur, which are not migrating. They owe their segregation to a shepherding or tidying effect of winds (from various directions) which has kept such sand as has been available neatly piled in heaps. The source of supply of this sand has been deflation of local soils.[45] These dunes are generally covered on the flanks by anchoring vegetation, but have loose tops. An enormously increased supply of drifting sand of local origin has made its appearance in recent droughts. This is to a much smaller extent due to reversion of fixed to wandering dunes than it is to accelerated deflation of the soil on surrounding plains, which have been depleted of protective vegetation by grazing animals.[46]

Loess

Fine dust is exported by wind in vast quantities from dry deserts. After being whirled into the air by desert storms innumerable times, and eventually escaping over the border of the dry region, it is variously disposed of. Quantities of such dust carried westward by winds from Africa are known to fall in the Atlantic Ocean, and films of red dust observed in southern New Zealand have been traced to their source in the interior of Australia, two thousand miles away. Much of the dust must fall to the ground and be washed down by rain into the rivers of humid regions. In steppe-climate regions to leeward of deserts thick, fine-textured soils accumulate, however, which are apparently of aeolian origin. The cotton soil of the eastern Sudan, which is in places up to 100 feet thick seems to have been derived thus from Sahara dust,[47] and a similar aeolian origin is claimed for the productive Palouse soil of the Columbia Plateau of Washington.[48]

[43] C. T. Madigan, *loc. cit.* (41), pp. 513-5.
[44] R. A. Bagnold, *loc. cit.* (5), p. 124.
[45] F. Ratcliffe, *Flying Fox and Drifting Sand*, pp. 300-304, 1938.
[46] F. Ratcliffe, *loc. cit.* (45).
[47] W. H. Hobbs, *loc. cit.* (3), p. 57.
[48] K. Bryan, The "Palouse-soil" Problem, *U.S. Geol. Surv. Bull.*, 790-B, pp. 21-45, 1927.

To leeward (eastward) of the vast Gobi Desert region the accumulation of dust in a thick layer almost universally overspreading the landscape of northern China is a fact that is rarely disputed. When the dust particles alight in a grass-clothed steppe region their chances of being held in place by the vegetation are considerable, and such is believed to be the mode of origin of the fine-grained superficial "loess" found not only in China but in many other regions also. The dust that forms loess, however, is not all of desert origin; much of it originated in the Glacial Period, when rivers of melt-water laden with the rock flour ground from debris and bedrock under glaciers spread this powder widely at times of flood over outwash aprons and valley trains, to be dried and wafted on its way as dust by ensuing gales, as may be observed even to-day in valleys traversed by rivers of glacial melt-water in New Zealand, Patagonia,[49] and Alaska,[50] where loess is now accumulating.

Any discussion of the texture and structure of loess regarded as a geological formation or rock entity would be beyond the scope of a work on landforms. Much has been written on the subject, however, and the aeolian theory of the origin of the material, which was proposed by Richthofen,[51] has more recently been convincingly maintained by Barbour.[52] In fairness, however, to a convinced opponent of the aeolian loess theory passing mention must be made of Berg's theory that the formations generally believed to consist of wind-deposited dust and termed "loess" have not been spread superficially by wind or other agency, but are in reality residual products of weathering and soil-making processes working upon "the most various fine-grained rocks rich in lime carbonates . . . . in the condition of a dry climate."[53]

[49] Arnold Heim, *Die Alpen,* Aug. 1940 (review in *Geog. Jour.,* 97, p. 132, 1941).

[50] R. Tuck, The Loess of the Matanuska Valley, Alaska, *Jour. Geol.,* 46, pp. 647-53, 1938.

[51] F. von Richthofen, *China,* Vol. 1, pp. 56-125, Berlin: 1877.

[52] G. B. Barbour, The Loess of China, *Smithsonian Rep. for 1926,* pp. 279-96, 1927 (reprinted from *China Journal of Science and Arts,* 3, pp. 454-63, 509-19, 1925); Pleistocene History of the Huangho, *Bull. Geol. Soc. Am.,* 44, pp. 1143-1160, 1933.

[53] L. S. Berg, On the Origin of Loess (in Russian), *Izvestiya of the Russian Geographical Society,* 52, pp. 579-647, 1916; The Origin of Loess, *Gerlands Beitrage zur Geophysik,* 35, pp. 130-50, 1932.

As a landscape-making agency dust accumulation does not produce spectacular results. Heights and hollows of buried landscapes have been built up rather uniformly. Land surfaces not only in China but also in Europe, North America, and southern New Zealand are composed of loess to depths varying up to scores and (in China) perhaps even hundreds of feet. Many loess deposits form plains, and the material is associated with water-laid fluvio-glacial outwash. In New Zealand loess has built up the landscape surface over a lava plateau (at Timaru) and over an aggraded plain of river gravels (at Oamaru), both of which are now cliffed at the margins so as to show the superposition of the loess very clearly. Loess also covers maturely undulating land surfaces developed on various terrains.

Fig. 41. Natural causeway between gullies in the loess of China. (From a sketch by G. B. Barbour.)

When dissected owing to a revival of erosion, loess, though it is a weak pulverulent material, rarely slumps or crumbles away after the manner of residual clay which it sometimes resembles in appearance. On the contrary, being permeable and always traversed by an obscure vertical parting, it tends when trenched and undercut by erosion to form vertical cliffs. Thus in China the loess region is dissected by many vertical walled and steep-headed canyons, narrow causeways of the constructional loess surface are left between adjacent canyons (Fig. 41), and parts of these even survive as natural arches (Fig. 42).[53a] According to Woiekof[54] the erosion and

[53a] See M. L. Fuller, *Geog. Rev.*, 12, pp. 570-584, 1922.

[54] A. Woiekof, De l'influence de l'homme sur la terre, *Ann. de Géog.*, 10, pp. 97-114, 193-215, 1901.

dissection of the loess from which the Huangho (primitively a "black" river) derives most of its abundant silt, is entirely a result of man's interference with the natural landscape; but this is an unproved assertion.

The ubiquitous vertical parting in loess, which controls the character of the landscape forms that result from its erosion, is one of its most striking properties (together with the invariably fine grain, angularity, and undecayed condition of its constituent particles, the absence of colloid clay, the abundance of lime carbonate, and the high permeability of the material). The parting has been regarded since it was observed by Richthofen as related in some way

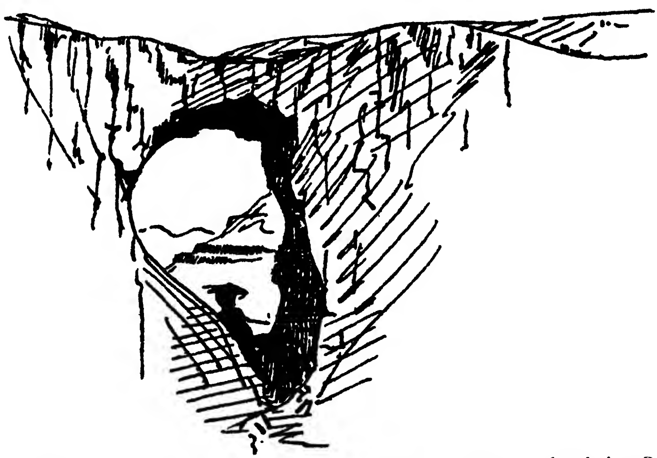

Fig. 42. Natural arch in loess, Wanch'üanhsien, China. (From a sketch by G. B. Barbour.)

to the mode of accumulation of loess-forming dust particles around growing vegetation. It has been explained in conformity with the hypothesis of aeolian deposition as the result of combination of the following important factors operating during its accumulation:

> (1) Continued abundant growth of steppe vegetation, especially grass and bent; (2) contemporaneous and steady supply of fine dust which was carried into the region by winds and settled to the ground, where it was protected by the vegetation from further disturbance and became part of the permanent soil mantle; (3) subsequent destruction of all traces

of such pre-existing vegetation under climatic and ground conditions that led to the almost complete oxidation of the organic matter.

The principal factor in such destruction is apparently oft-repeated moistening followed by drying and access of fresh air, just as happens when rain waters percolate through the loose ground above the permanent water level in a region of moderate but frequent rains.[55]

Lunettes

Actual hill forms built up by dust accumulation from level surfaces have been described in south-eastern Australia (Victoria). Originally termed "loam ridges," they have been more recently re-named "lunettes" by Hills on account of their crescentic outlines in ground plan[56] (Fig. 43).

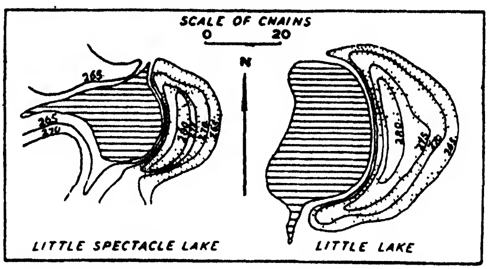

Fig. 43. Relation of typical small lunettes to lakes, Victoria, Australia. (After Hills).

These Victorian lunettes are composed of a black loam formed as a result of precipitation from the atmosphere of fine dust most of which must have been brought by strong winds from a great distance. They are closely associated with lakes and occasionally flooded swampy areas, rising just to leeward (eastward) of these and half encircling them. During gales, when the air is dust-laden, dust is captured and brought down by spray whipped up from the lakes and thus a deposit accumulates close to the lee margin of the lake.

[55] C. P. Berkey in G. B. Barbour, *loc. cit.* (50), p. 295.

[56] E. S. Hills, The Physiography of North-western Victoria, *Proc. Roy. Soc. Vic.*, 51, pp. 312-4, 1939; The Lunette, a New Landform of Aeolian Origin, *Australian Geographer*, 3 (No. 7), 7 pp., 1940.

Lunettes are generally several miles long and average about half a mile broad. Though only 20 to 30 feet high, they are prominent enough to be rather conspicuous features on a plain. They have "regular and smooth contours quite unlike those of sand dunes" (HILLS). Migration of the shallow lakes has in some cases resulted in the formation of successive parallel lunettes.

SECTION II

GLACIATED LANDSCAPES

CHAPTER X

Ice Sheets and Glaciers; Flow of Ice

THE ice of which glaciers are composed streams slowly down from higher to lower levels. Apart from this gravity-controlled flow in the form of sheets or streams, however, glaciers present no close resemblance to rivers of water. Originating in snowfields, they dispose of snow that must otherwise accumulate in vast piles wherever the annual precipitation in this form is in excess of the amount disposed of by summer melting, whether on and among high mountains or at lower levels in the polar regions. Above a level termed the "snow-line," the height of which above sea-level varies from zero in the polar regions to about 17,000 feet near the Equator, snow lies from year to year, forming permanent snowfields. The majority of such snowfields cradled among mountains, whether they give rise to definite narrower outflowing ice streams ("glacier tongues") or not, are to be regarded as glaciers or as parts of glaciers. They are termed "névés," and the granular, somewhat recrystallised snow in them (termed "firn")[1] has already assumed some movement under the influence of gravity. An important part of the erosion ascribed to glacial action is work done by the normal freeze-and-thaw rock-breaking process working in close association with névés.

THE GLACIAL PERIOD

Relatively small parts of the land surface outside the polar regions are to-day ice-covered, but in the Ice Age or Glacial Period an extension of glaciers took place in regions that are now temperate

[1] Firn and névé are terms originally synonymous, derived from German and French respectively, which are becoming conveniently specialised by usage as defined in the text.

and ice-free, as is evident from the abundance of characteristically ice-worn landscape forms, as well as from the presence of widespread glacial deposits. Such features are termed "glaciation," and so also, quite commonly, is the "ice flood" which has been the cause of their development. An attempt has been made, however, to introduce the term "glacierisation" for an ice flood without implication of its geomorphic results.[2] The glaciation, or glacierisation, was compound, for there are clear indications that during the long extent of the Glacial Period several ice floods occurred in "glacial epochs" which were separated by "interglacial epochs" of mild climate. So recently did the last glacial epoch come to an end that the landscape forms carved by its glaciers and the features built in it of glacier-carried debris have been as yet but little modified by normal erosion in "postglacial" time.

There is less essential difference than might at first appear between the discontinuous glaciers present among mountains in cool temperate regions and the continuous "ice sheets" or "continental glaciers" which are now restricted to Greenland and Antarctica but which covered great parts of North America and northern Europe in the glacial epochs of the Ice Age. Local "ice caps," or "plateau glaciers," in Iceland, Norway, and Arctic islands, which rest on uplands of small relief and spill in places as tongues over their margins, bridge the gap to some extent between the extreme glacier types.

Mountain-and-Valley Glaciers

The discontinuous glaciers found at the present day among mountains may be classed as "valley" glaciers and "hanging" glaciers. In the former the ice flowing out from a névé (Pl. XI, 1) continues on as an elongated glacier tongue which extends down a valley (Pl. XII, 2) to a level in some cases very far below the snow-line. Eventually, however, the glacier tongue (unless it is in a high latitude, where it may thrust out into the sea) dwindles as its ice wastes away rapidly at lower levels and comes to an end, giving rise to, or being continued by, a river of melt-water.

A main valley glacier commonly receives tributary ice streams, often referred to as "secondaries," and its volume is further

[2] C. S. Wright and R. E. Priestley, *Glaciology*, British Antarctic Exped. 1910-13, p. 134, 1922.

augmented in its upper or headward part (zone of "alimentation") by falls of snow on its surface, by slides of snow descending as snow avalanches from the valley sides, and by avalanches of firn and of true glacier ice from hanging glaciers that thrust forward from niches overhanging the main valley (Pls. XI, 2; XIII, 1).

Hanging glaciers, which are small and numerous in many mountain regions, consist practically of a névé only. Equally with glacier tongues, however, they are endowed with the faculty of forward motion on declivities. They perch on mountain shelves and rest in deeply worn amphitheatres ("cirques" or "corries") high up on valley sides, the explanation of the origin of which is one of the problems of glacial erosion (Chapters XIII-XV). A hanging glacier may or may not extend to the outer edge of the niche that contains it. If it does so and thrusts over the lip, the firn or glacier ice of which it is composed breaks away at the margin and slides or falls as frequently recurring avalanches to form perhaps a "reconstructed" (or "remanié") glacier on a lower shelf (Pl. XIII, 1), to melt each summer on a valley side, or to swell the volume of a valley glacier that may be present below it (Pl. XI, 2).

Some glaciers now hanging may in the future be extended by developing tongues; and obviously a great many of the hanging glaciers of to-day in mountain regions such as those of Switzerland and the South Island of New Zealand have in the past spilled over the lips of their niches as continuous ice streams instead of discharging, as they do now, as ice avalanches. In some mountain regions small hanging glacier remnants in valley-head cirques might be regarded as the last surviving portions of the full-bodied trunk glaciers of a former age. Such, for example, are the glaciers of the Sierra Nevada of California.

Another view with regard to these, however, is that the glaciers of the last glacial epoch of the Ice Age melted away completely thousands of years ago in a warm epoch, of which confirmatory evidence is available, and that the small glaciers now occupying valley-head cirques are of more modern development as a recrudescence of glacial conditions—a modern "Little Ice Age," as it has been termed.[3]

[3] F. Matthes, Committee on Glaciers, 1939-40, *Trans. 1940 Am. Geophys. Union*, pp. 396-406, 1940.

"Ice-falls," which are steep and obviously thin tongues of crevassed ice (Pls. XIII, 2; XV, 1), now mantle some steep valley-side slopes as extensions of almost-hanging glaciers in high niches, converting them into a semblance of secondaries.

A hanging glacier as a whole is homologous with the head of a valley glacier. In the latter the glacier tongue is commonly narrower at its commencement than the névé, has an appreciable slope (steeper than that of the névé), and may be confined between rock walls in a deep trench. While the cross profile of a névé is concave that of an ice tongue is convex, though not strongly convex in the case of large glaciers, which have surfaces almost quite flat from side to side, as has been pointed out by Blache.[4] Concavity of the névé surface indicates that it is still being fed with snow at the sides by avalanches (is in the zone of alimentation, that is to say) whereas the tongue, or at least a great part of it, is being wasted by melting and evaporation more rapidly than it is thus fed. (It is in the zone of "ablation," which begins in the vicinity of the snow-line).

The resemblance between the "trough" or channel in which a glacier tongue flows and the immediate channel (between banks) of a river is not close, for a glacier has an enormously greater cross-section than an equivalent river because of its very slow rate of movement. It is hundreds (quite commonly thousands) of feet deep, and its width may be measurable in miles.

Glacier Ice

Though the superficial layers on a névé retain the appearance and open texture of snow, buried layers are more granular owing to conversion of snow into firn. Spheroidal grains of ice—each a crystal—are in course of formation in the firn by recrystallisation at the expense of the feathery skeleton crystals of the original snow, and deeper layers are progressively denser and more compact as the amount of entangled air they contain becomes less.

The major part of the transformation from porous firn to glacier ice, impermeable to water, is accomplished perhaps in the course of a deep submergence beneath the névé which much of the firn seems to undergo, according to observations carried out over a

[4] J. Blache, *C-R. XV Congr. Internat. de Géogr.*, 2, p. 18, 1938.

period of many years on the Clarinden névé by Streiff-Becker.[5] Measurements of the rate of accumulation and evacuation of the firn indicate that it flows out from the névé in a stream the velocity of which is greatest at the bottom, so that firn layers are tilted backward and their rear edges become submerged to the full depth of the névé. Where the ice emerges again in the glacier tongue it is compact and consists of coarse crystal grains well fitted together. Farther down-valley in a long tongue continued recrystallisation of the granular ice is attested by increasing coarseness of grain until crystals of three to four inches, and even six inches, in diameter may be present, as noted by R. T. Chamberlin.

In the glacier tongue, though all the ice is compact and contains little entangled air, layers of white ice (containing some air bubbles) generally alternate with layers of clear ice. Some such banding may be a relic of original stratification in the névé, such as marks off the snows of successive years. Stratified layers of firn are parallel (roughly horizontal) at first, but become tilted and deformed by the flow of the firn; and the banding resulting from stratification, if, as some observers hold, it is recognisable in distal parts of the glacier tongue,[6] has become crumpled and distorted there, possibly as a result of contraction in the cross-section of the glacier tongue as compared with that of the névé.[7] Other banding structures are present in glaciers, however, which result from shearing (p. 132).

Glacier Motion

Both firn and glacial ice flow outward from the centres of accumulation and make their way down slopes at rates varying from a fraction of an inch to many feet per day. The velocity of this movement depends in part upon the steepness of the declivity on which the material rests; but an important controlling factor in all cases is the volume of snow that has to be disposed of, which depends on the area of the gathering ground and on the precipitation.

[5] R. Streiff-Becker, Zur Dynamik des Firneises, *Zeits. f. Gletscherk.*, 26, pp. 1-21, 1938.

[6] "Beyond serious question the general stratification has its initial stages in the original snowfalls" (T. C. Chamberlin, Recent Glacial Studies in Greenland, *Bull. Geol. Soc. Am.*, 6, p. 205, 1895).

[7] H. Crammer, Zur Entstehung der Blätterstruktur der Gletscher aus der Firnschichtung, *Zeits. f. Gletscherk.*, 2, pp. 178-212, 1908.

The flow of ice is due in all cases to gravity. The actual movement may be brought about, however, either by a hydrostatic head or by a gradient of the floor on which the ice rests. The former results from up-piling of firn, the weight of which causes compressive stress and leads to outward movement from the centre of accumulation even over a horizontal floor and (for short distances) uphill. In moving under the compulsion of hydrostatic pressure the ice is in compression; but where movement is down a gradient of the floor under the direct influence of gravity most parts of an ice stream are in tension.

This tension causes the remarkable broad and deep dimples ("basins of exudation"[8]) in the surfaces of some ice sheets at the heads of the "outlet glaciers" by way of which—as in Greenland and Antarctica—they overflow through gaps in imprisoning mountain rims. The gravity stream in an outlet glacier tends to suck ice away more rapidly than it can be supplied by hydrostatic pressure from the centre of accumulation and maintain a smooth surface. So thin has the ice become as a result of this induced surface concavity in many exudation basins that its surface takes on a considerable degree of relief which indicates that the thinned stream is passing over an uneven floor.[9]

Easily made measurements and observations indicate that the rate of movement in a glacier is not the same throughout its width, but is more rapid in the middle than at the sides, and it is known also that the velocity of movement diminishes downward also as the glacier bed is approached. It is obvious, therefore, that glacier movement is not a mere sliding of a rigid body of ice down a declivity, but that some kind of actual flow is in progress—that the glacier ice, though crystalline, flows somewhat after the manner of a viscous fluid, being retarded by friction along the sides and bottom of its channel.

Striation of the rock floors over which former valley glaciers and more especially continental ice sheets have moved also indicates that the ice has commonly had great mobility of flow.[10] It has long

[8] R. E. Peary, Journeys in North Greenland, *Geog. Jour.*, 11, p. 232, 1898.

[9] M. Demorest, Glaciation of the Upper Nugssuak Peninsula, W. Greenland, *Zeits. f. Gletscherk.*, 25, p. 48, 1937.

[10] T. C. Chamberlin, The Rock-scorings of the Great Ice Invasions, *U.S. Geol. Surv. Am. Rep.*, 7, pp. 155-248, 1888.

been known that the basal parts of thick continental ice-sheets had this mobility, but such pseudo-viscous flow has been proved also in the case of a small valley-head glacier (Clements Glacier, Glacier National Park) studied by Demorest.[11] Scratches made by rock debris dragged by the ice over the rock floor under this glacier prior to a shrinkage of the ice which has recently exposed the rocks are found to indicate great intricacy of flow, differential velocities, even "eddy-like currents in the ice," and above all continuous contact of ice with rock where the glacier has passed over highly irregular surfaces with sharp re-entering angles, and where the thickness of overlying ice cannot have been greater than about 150 feet.

Such flow of crystalline material, in which the configuration of repeating patterns of atoms within each crystal must be maintained, is essentially different from the flow of a non-crystalline though solid substance such as pitch, and cannot be explained as simply. Rotation of ice grains, if it could take place, would allow the glacier to progress like a quantity of shot or ball-bearings, and it has been calculated that only a very small amount of rotation of each grain would give the mass the required mobility.[12] The problem is not as simple as this, however, for the grains cannot roll freely, being closely fitted together and interlocked except in early stages of their development in the firn. Partial melting of grains at projecting points where the greatest stresses are felt is an obvious possibility, and any such melting will be followed by refreezing in crystal continuity with existing grains as stresses are relieved, and in this way some rotation of grains may occur.

Glacier ice resembles some crystalline rocks in texture, and deformation of deep-seated rocks is known to involve actual flow, though only under very great pressure. In part at least it is a matter of slow rearrangement by recrystallisation of the minerals composing the rock, and the transfer of molecules from one part of a crystal to another and from one crystal to another requires the

[11] M. Demorest, Ice Flowage as Revealed by Glacial Striae, *Jour. Geol.,* 46, pp. 700-725, 1938.

[12] To account for a movement of 3 ft. per day in a glacier six miles long the mean motion of the average granule would be, roundly 1/10,000 of its own diameter per day, or one diameter in 10,000 days (T. C. Chamberlin and R. D. Salisbury, *Geology.,* Vol. 1, p. 314, 1906).

presence of some intergranular fluid medium. The flow of the granular ice of glaciers is very probably of the same general nature as rock flow, but the processes are probably not strictly homologous, for ice, unlike rock constituents, has its melting-point lowered by pressure, and its temperature in a glacier is usually near the melting-point. The much lower pressures under which ice flow becomes possible, as compared with rock flow, and the relatively rapid rate at which the pattern of ice crystals must change its configuration are to be explained, no doubt, by the contrast in physical properties between ice and the minerals of crystalline rocks.

The hypothesis that in glaciers "movement takes place by the minute individual movements of the grains upon one another" was advanced by T. C. Chamberlin.[13] "While they are in the spheroidal form, as in the névé, this would not seem to be at all difficult. They may rotate and slide over each other as the weight of the snow increases;[14] but as they become interlocked by growth both rotation and sliding must apparently encounter more resistance. The amount of rotary motion required of an individual granule is, however, surprisingly small, and the meltings and freezings incident to shifting pressures and tensions, and to the growth of the granules, seem adequate to meet the requirements. . . . However slight the relative motion of one granule on its neighbour, the granules in any part of a glacier partake in the accumulated motion of all parts nearer the source, and hence all are thrust forward. Herein appears to lie the distinctive nature of glacial movement."[15]

From the fact that glaciers in polar regions flow more rapidly in summer it has been inferred that the presence of melt-water greatly facilitates movement, not only acting as a "lubricant," but furnishing, according to Chamberlin, the necessary medium for the transfer of molecules from one crystal to another in the constantly recurring process of recrystallisation. Thus, in the region of ablation at least, "the average temperature is near the melting-point, and during the warm season the ice is bathed in water, so that the necessary changes in the ice crystals are facilitated." On

[13] T. C. Chamberlin, A Contribution to the Theory of Glacial Motion, *Univ. Chicago Dec. Publ.*, 9, 1904.

[14] Movement of this nature has been observed in the firn of the Aletsch Glacier (Jungfraujoch Research Expedition, *Geog. Jour.*, 93, pp. 346-347, 1939).

[15] Chamberlin and Salisbury, *loc. cit.* (12), p. 314.

the other hand, where firn and ice are very cold and dry, movement may be delayed. "Compression must be great before it becomes effective in melting the ice, and hence the great thickness of the mass antecedent to much motion . . . . *A dry glacier is a rigid glacier. A dry glacier is necessarily cold, and a cold glacier is necessarily dry.* . . . A glacier should be more rigid in winter than in summer."[16]

It has been thought by various authors[17] that instead of pure water a thin film of a solution of sodium chloride may be present between the grains of glacier ice. An explanation of the source of such salt does not present great difficulty. A considerable portion of it may be derived from dried ocean spray blown inland and there washed out of the atmosphere by rain or snow. In relatively dry ice a small amount of salt may be present along with a minute quantity of water as a fairly concentrated solution. The freezing-point of such brine is very low and it will remain liquid at ordinary glacier temperatures—even in glaciers that are too cold to be permeated by melt-water.[18]

Recorded observations indicate that the temperature of the ice in most glaciers in temperate regions (at depths greater than that, 50 feet at most, to which winter cold penetrates from the surface) is in the vicinity of the melting-point appropriate to the depth as calculated from the weight of overlying ice.[19] Even in regions of very low surface temperature this condition obtains under a considerable depth of ice owing to conduction of heat from the earth, though nearer the surface the ice is very cold, maintaining approximately the mean air temperature of the locality.[20]

Heat conducted from the earth will keep the temperature in all

[16] Chamberlin and Salisbury, *loc. cit.* [(12)], p. 320.

[17] Buchanan, O. D. von Engeln, and, later, H. Hess (Das Eis der Erde, *Handbuch der Geophysik*, 7 (1), 1933).

[18] Investigators have failed to detect the presence of any salt in glacier ice, but the same investigators have recorded the fact that flow accompanied by recrystallisation is in progress in high-altitude glacier ice which remains continuously at a temperature far below the melting-point (Perutz and Seligman, A Crystallographic Investigation of Glacier Structure and the Mechanism of Glacier Flow, *Proc. Roy. Soc.*, A172, pp. 335-360, 1939).

[19] Perutz and Seligman, *loc. cit.* [(18)].

[20] E. Antevs (*The Last Glaciation*, p. 69, 1928) estimates that the temperature increases downward (until it closely approaches the pressure-determined melting-point) at a rate of 1° C in 15 to 20 metres.

thick glaciers up to the pressure-determined melting-point at the bottom of the ice and will raise that of overlying ice to but not above the same temperature.

In ice above the basal layer the melting-point is higher, however, and so glacier ice must commonly be at temperatures slightly below the actual melting-point of the ice, but sufficiently high to be above the solidifying temperature of such brine films as may be present between crystals.[21]

The flow of a glacier assumed to consist of granular crystals well fitted together without any open pore space, but made mobile by the presence of extremely thin intervening films of liquid brine, so that crystals are not only subject to recrystallisation, but are to a very slight extent "loose in the socket," has been visualised by von Engeln as a "wallowing" down its valley. More lately, however, this author has come to regard glacier ice as less mobile than the term "wallowing" would imply.[22]

It has been observed that glaciers in very cold regions (the "high-arctic" type of Ahlmann[23]) are more rigid than those of more temperate climates, though they are not without some mobility, and in some cases flow rapidly. Whereas in most glaciers the ice of a secondary merges rather obviously with that of the main below a junction, glacier tongues in extremely cold regions fail to coalesce and below junctions flow side by side or overlapping one another.[24] This is obviously a result of low-temperature rigidity. Such glaciers are dry—that is, do not contain melt-water—as the temperature in the body of the ice (except in the basal parts of thick glaciers) is always considerably below the melting-point.

A considerable measure of rigidity has been ascribed by both T. C. and R. T. Chamberlin to ice even in the bottom layers of the deepest glaciers. Though they have favoured hypotheses of granular flow, both have maintained that the mobility of an ice stream must

[21] O. D. von Engeln, Experimental Studies of Ice with Reference to Glacier Structure and Motion, *Zeits. f. Gletscherk.*, 9, pp. 81-139, 1915.

[22] O. D. von Engeln, The Motion of Glaciers, *Science*, 80, pp. 401-403, 1934; *ibid.*, 81, pp. 459-61, 1935; Glacial Geomorphology and Glacier Motion, *Am. Jour. Sci.*, 35, pp. 426-440, 1938.

[23] H. W. Ahlmann, Contribution to the Physics of Glaciers, *Geog. Jour.*, 86, pp. 97-113, 1935.

[24] N. E. Odell, The Glaciers and Morphology of the Franz Josef Region of North-east Greenland, *Geog. Jour.*, 90, pp. 111-125, 233-258, 1937.

be considered far from perfect in order to explain glacial abrasion of bedrock—though, in reply, the analogy has been put forward that a metal surface may be scratched by abrasive particles "on the under side of a cake of beeswax."[25]

A quantitatively important element in differential glacial movement which implies rigidity of the ice is, as claimed by R. T. Chamberlin,[26] "solid shearing of aggregates of granules. This small-scale faulting is found to be more prevalent and general than are larger slips on well-developed thrust planes, and is a characteristic feature of glaciers." He finds the traces of shear movement in the prevalent banding of the ice of a glacier tongue which others have attributed to close plication of the stratified layers resulting from successive falls of snow or seasonal snows on the névé (p. 126). This structure is interpreted by Chamberlin as a kind of foliation or gneissic banding developed after the glacier ice has passed through a condition of granular crystallisation corresponding to that of a crystalline limestone and assumed that of a metamorphic rock.[27]

> In the portions of the glacier where the ice has already moved for considerable distances, particularly in the lower ice tongue, a distinct cleavage and banding are manifest . . . The strike of these structures closely parallels the margin of the ice tongue and the dip is inward towards the middle of the moving mass. Along the side of a long ice tongue the banding stands at a high angle, as a rule, and in places becomes vertical, but near the terminus it is inclined at considerably less than 45° . . .
>
> The cleavage consists of a large number of shear planes along each of which the ice above has moved forward and upward over that below. The movement is simplest near the snout of the glacier. Here . . . the upper ice rides forward along shearing planes inclined at relatively low angles. Along the sides of a long glacier confined between valley sides there is some movement towards the margins to replace wastage, but there is a stronger component of movement down the valley parallel to the confining walls. Consequently the shear planes

[25] O. D. von Engeln, The Motion of Glaciers, *Science*, 81, pp. 459-461, 1935.

[26] R. T. Chamberlin, Instrumental Work on the Nature of Glacier Motion, *Jour. Geol.*, 36, pp. 1-30, 1928; The Motion of Glaciers, *Science*, 80, p. 526, 1934.

[27] R. T. Chamberlin, Glacier Movement as Typical Rock Deformation, *Jour. Geol.*, 44, pp. 93-104, 1936.

> here parallel the glacier margins in strike, but are very steeply inclined or even vertical.
>
> Some of the shear planes are visible only as fractures and surfaces of slippage; others are made more apparent by slight accumulations of fine debris along them. Along some the movement has doubtless been slight, but along others it has obviously been very pronounced . . .
>
> Paralleling the fracture cleavage, except where more than one episode of deformation under differently oriented stresses is apparent, is a banding which consists of layers of whitish ice containing numerous small air bubbles and other layers of bluish ice relatively free from bubbles. The blue bands are thinner than the white bands and seem to represent old shearing planes along which water has subsequently frozen and from which the air bubbles have been largely expelled. The blue bands are particularly useful as recorders of deformation . . .[28]

In brief, it is urged by Chamberlin that glacier movement is closely homologous with rock deformation by "solid-rock flow," in which "recrystallisation, granulation, and adjustment of granulated particles, gliding of crystals where possible, and shearing of various sorts" all take part. "The summation of these individual movements and adjustments is movement of the mass in the direction of easiest relief."

The superficial ice of a glacier tongue differs from the deeper flowing ice in that it behaves more like a rock in the superficial "zone of fracture," and tension cracks, which become crevasses in the ice of the glacier, here correspond to the joints and faults developing in rocks that are subject to deformation though not deeply buried. It must be realised, however, that ice now at the surface and in the zone of fracture and tensional fissuring has been exposed there by surface melting after having previously formed part of the deeper stream, and thus it may exhibit the truncated edges of folded banded structures. This is closely analogous with

[28] R. T. Chamberlin, *loc. cit.* (27). Investigation of the ice in blue bands has confirmed Chamberlin's view. Some of these "represent thrust planes and are caused by laminar motion of large strata of ice," though other blue bands have been seen which are "old [stratification] ice bands originally present in the névé" (Perutz and Seligman, *loc. cit.* (18)).

the exposure by erosion of deformed rocks with a complicated structure pattern.[29]

The shallow zone of ice subject to crevassing, with a depth of 200 feet[30] at most, may perhaps be thought of as a relatively rigid (or brittle) layer borne along bodily on the back of the deeper, relatively plastic ice stream, though it would be rash to deny that true flow can take place even in superficial ice. R. T. Chamberlin discredits the theory of sharp demarcation or very rapid transition between zones of fracture and flow either in glacier ice or the rocks of the lithosphere. He regards as illusory, indeed, the whole concept of such zones unless these terms are considered to imply merely a "zone of cavities" contrasted with a "zone of continuity." Crevasses can be opened only in the superficial zone of ice in which cavities can be formed, just as joints and tension faults can develop in rocks at shallow depths. In the deeper ice crystalline flow takes place, reinforced to an extent as yet quantitatively undetermined by the shearing which Chamberlin finds associated with the development of cleavage and banding. This process "does not require separation" —that is to say, does not involve the breaking of continuity or opening of cavities.[31]

Chamberlin's composite theory of glacier movement recognises also some "sliding of the whole body of the ice over the rock beneath" and "intermittent slip along well-developed thrust planes."[32] The former of these is attested by striation, grooving, and fluting of the underlying rock surface. "The length and depth of some of the individual scratches would seem to indicate that the rock fragments which cut them were firmly held by the moving

[29] "The glacier may be regarded as made up of two layers—a superficial, relatively rigid layer, and a basal layer, mobile under the weight of the other; or of a zone of fracture and a zone of flow. In the thinning frontal region the upper layer, or cover, is brought into contact with the bed. Rearward it is lifted; though at the same time there it is planed away. Hence rising lines of flow in effect extend to the surface; for the cover is to be regarded as a zone of rigidity merely, constant only as to position, and thickening from the mobile ice below as it is thinned by ablation above" (Willard D. Johnson, The Profile of Maturity in Alpine Glaciation, *Jour. Geol.*, 12, pp. 569-578, 1904).

[30] Seismic sounding on South Crillon and Klooch glaciers, Alaska (R. P. Goldthwait, *Geog. Jour.* 87, pp. 496-517, 1936) has indicated that the maximum depth of actual crevassing is only about 100 feet, but a boundary between "low-velocity" and "high-velocity" ice is present at an average depth of 170 feet.

[31] R. T. Chamberlin, *loc. cit.* (27).

[32] R. T. Chamberlin, *loc. cit.* (26) (1934).

ice for considerable lengths of time." T. C. Chamberlin envisaged the ice immobilised by a very low temperature when thus firmly holding the stones it uses as graving tools. "They may be rotated with relative ease when the ice is wet."

R. T. Chamberlin's "intermittent slip along well-developed thrust planes" is the process of forward translation of slices of the upper ice along flat-lying surfaces of dislocation comparable to thrust planes among rock structures and sometimes termed "shearing" planes in glaciers. They are better termed "thrust planes," however, to distinguish them from more steeply inclined planes of shearing in the glacier. They have been observed more especially where the ice has already made its way down to lower levels and are conspicuous in the ice of some glaciers where exposed in cliffs near the snout or terminal face, being revealed in some cases by the emergence of, or differential melting along, a layer of debris which has been forced into them by the shearing movement. The occurrence of horizontal shearing perhaps implies no more than a failure of granular flow to relieve stresses and accomplish forward movement in the upper brittle "crust" of the glacier, especially where this reaches to the base at the thin edges. In the snout of a glacier, especially, this crust is thrust forward by the stream of thicker ice at its rear, and yields by shearing along nearly horizontal thrust planes.

Ice crystals shear very readily along gliding planes at right angles to the chief crystallographic axis. Unlike the crystals of pond ice, which have a parallel orientation, the granular crystals of glacier ice lie with axes pointing in every direction, rarely exhibiting such an approach to parallel orientation as would permit easy shearing through parallel gliding planes of adjacent crystals. Some observations show, however, that owing to recrystallisation there is a tendency towards the adoption of a parallel arrangement (with chief axes vertical) in the ice of the glacier tongue, thus facilitating the development of the thrust planes seen near the terminal face. It cannot be suggested seriously, however, that crystals rotate into and retain this orientation during granular flow of the ice.

Study of the orientation of ice crystals in the névé and tongue of the Aletsch Glacier[33] has shown that most grains of firn when

[33] Perutz and Seligman, *loc. cit.* (18).

first developed have the chief axis perpendicular to the surface (that is, in the direction of the temperature gradient), but that this parallel arrangement of the crystals is destroyed later by "non-laminar" flow, which is described as a "haphazard motion of single crystals or clusters of single crystals." As a result, however, of recrystallisation taking place under the influence of shear in the vicinity of planes along which motion of the ice has been observed to be in progress a new orientation of crystals develops, which brings the basal (gliding) planes into the plane of shearing. In the process of recrystallisation it appears that those crystals with a favourable orientation grow at the expense of others. Thus it has been confirmed that the parallel orientation of crystals in the vicinity of shearing and thrust planes, while it facilitates shearing, has been brought about by the shearing stress. T. C. Chamberlin's idea of the mechanism of the process was as follows: "Those [crystals] whose gliding planes are parallel to the direction of thrust are strained with sufficient intensity to cause the plates to slide over each other, while those which are not parallel to the direction of thrust are either rotated into parallelism—when they also yield—or are pressed aside out of the plane of shear."[34]

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[34] Chamberlin and Salisbury, *loc. cit.* (12).

CHAPTER XI

Glaciers (continued)
Crevasses; Termini; & Morainic Debris

IN THE FOREGOING chapter on glaciers only passing mention has been made of "crevasses," those frequently-occurring tension cracks in the superficial ice which constantly remind the Alpinist of glacier motion. The question of the depth to which crevasses extend is of considerable importance in the discussion of the hypotheses of glacial erosion; for authorities have not all been in agreement that on deep glaciers tension cracks are only superficial features (p. 134). Many glacialists have thought that crevasses might extend to the bottom of any glacier.[1] It is now generally agreed, however, that they are confined to the brittle crust which rides (in the case of a deep glacier) on the deeper, more plastic ice stream; they are phenomena of the "zone of cavities." The upper crust is torn apart wherever tension develops as a result of the deep differential flow.

One frequent cause of the formation of crevasses, perhaps more affecting the thin, shrunken glaciers of to-day than their more robust and thicker predecessors of the Glacial Period, is the occurrence of breaks of slope in the surface of bedrock underlying the ice. Longitudinal bedrock profiles, as revealed by the shrinkage or complete disappearance of glaciers from the valleys they have occupied (Pl. XX, 2) are found to be very irregular. Sharp descents alternate with reaches that are roughly horizontal or are even hollowed out as rock basins. While there is a progressive down-valley gradient sufficient to cause ice to flow, the basal stream of ice in such a valley must move on an upgrade, and even the surface slope is reversed in a few known cases for a short distance, showing that a portion of the thin present-day glacier is being thrust uphill. This condition is occasionally found where glacier distributaries cross former divides. The upper crust of the glacier is in such a case compressed, as it is also in those parts affected by horizontal shearing; but where the rock floor descends steeply the crust is

[1] H. Hess, Das Eis der Erde, *Handbuch der Geophysik*, 7, 1933.

stretched by acceleration of flow, whether there is or is not a flowing stream of "plastic" ice under it, and close-set transverse crevasses are opened. Where also the ice stream turns a corner the brittle crust cracks open at right angles to the direction in which tension develops; and where a glacier has an "expanded foot," sprawling out fan-wise in front of a valley from which it debouches, or where, even in a névé, divergent flow takes place, longitudinal or radial crevasses are torn open as a result of lateral stretching of the surface ice as the deeper layer spreads outward (Pl. XIV, 1).

Glaciers descending very steep slopes are so broken by crevasses that they become "ice-falls" (Pls. XIII, 2; XV, 1), often with crowded ridges and pinnacles sharpened by ablation.[2]

Crevasses in Chevron Pattern

Even in a straight valley with an even floor crevassing, in this case in a regular pattern, results from differential rates of flow at middle and sides of the ice stream. The more rapid flow in the middle causes development in the brittle crust of tensile stresses directed from the centre line up-valley at angles of 45° with the sides, and of cracks, which open in response and also make 45° angles with the sides, though directed from the centre line down-valley. Some even-flowing glaciers exhibit a regular chevron, or "fish-bone," pattern of such crevasses a few feet apart (Pl. XIV, 2).

Crevasses when once opened remain open, or are perpetuated in the surface pattern of the ice by surface melting, until buried again by winter snows. Borne downstream they become distorted, showing the effects of differential flow. The ends of the arms of the Vs in the chevron pattern lag behind where the ice is retarded by valley-side frictional resistance. Pointing diagonally down-valley near the middle of the glacier they become more nearly transverse as the sides are approached, and close to the sides even curve around still farther and point up-valley (Fig. 44).

Where a glacier is broken into slices by numerous close-set crevasses its surface naturally becomes very uneven. Superficial irregularities when modified by ablation and so converted into sharp ridges and pinnacles are "seracs" (Pl. XV, 1).

[2] "Ablation" includes wastage by evaporation as well as melting.

Moulins and Moulin Potholes

"Moulins" are round well-like holes developed by local enlargement of crevasses by melting in the zone of ablation, and some moulins must extend through thin ice to the rock floor. "Moulin potholes" (Pl. XV, 2) are true water-cut potholes which have been made under glaciers in some way by streams of debris-laden water descending through moulins. Conditions for tension crevassing and the formation of moulins must recur at the same point, and so a succession of moulins in the ice stream may pass over a portion of

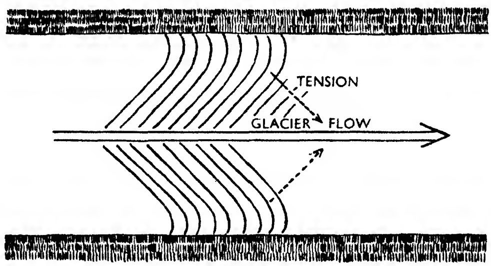

Fig. 44. The chevron pattern of crevasses on a glacier.

the rock floor. Hollows, irregular at first, excavated under these are eventually "deepened and assume the character of potholes. . . . After a hollow has been made and the condition for a whirl thus permanently localised, the whirl may be maintained by violent motion of the water anywhere about its rim, so that the deepening of the potholes progresses whenever a moulin stream strikes near it."[8] Moulin potholes are not very common but they are numerous and closely spaced in some places (e.g. in some valleys of the Sierra Nevada of California), and if they become confluent they wear down the rock surface in characteristic pothole fashion.

Subglacial River Corrasion?

The excavation of moulin potholes is a phase of subglacial water erosion, and the mention of it raises the question of the efficiency

[8] G. K. Gilbert, Moulin Work under Glaciers, *Bull. Geol. Soc. Am.*, 17, pp. 317-320, 1906. H. S. Alexander (Pothole Erosion, *Jour. Geol.*, 40, pp. 305-337, 1932) has pointed out that many supposed moulin potholes are in reality the results of postglacial stream work or were excavated by melt-water streams marginal to glaciers. Those described by Gilbert seem, however, to be genuine examples of subglacial erosion. See also M. Sauramo, The Quaternary Geology of Finland, *Bull. Com. Géol. Finl.*, 86, p. 39, 1929.

of water streams beneath the ice to erode. Where ravines and gorges now occupied by streams are found trenching broad valley floors that betray evidence of former occupation and perhaps sculpture by glaciers the question has sometimes arisen whether the present inner valleys and gorges occupied by rivers have been wholly cut by postglacial streams or whether they represent wholly or in part the work of water running under the ice.[4] Some investigators indeed have formed the opinion that streams of melt-water collected in subglacial channels are even more efficient eroding agents than the glaciers themselves and that the traces of their work are to be seen not only in trenching of valley floors but also in that general excavation of the glacier-occupied valleys which is usually attributed to erosion by the glaciers.[5]

It may be inferred on the contrary, however, from the abrupt step down, commonly showing scarcely a trace of a notch due to water erosion, which is generally found at the mouth of a glaciated hanging valley (Chapter XVII), that subglacial erosion by running water must have been entirely negligible during the formation of such features.[6] Absence of gorges through some of the rock bars ("riegels," Chapter XIX) across the floors of valleys which have been glacial channels, and the obvious youth and postglacial characteristics of the trenches through riegels when such gorges are present, supply a like indication that erosion by subglacial streams of water has been insignificant. If the existence of crevasses and open spaces is precluded by pressure and flow of ice except at depths of less than about 200 feet the hypothesis of infraglacial erosion by running water can have only a very limited application. It has been observed that thick glaciers of the present day do not have subglacial rivers draining melt-water from them along the axes of their valleys. Subglacial streams emerge only near their margins, where the ice is thin.[7] If any gorge-cutting beneath the ice is to be

[4] See, for example, D. Freshfield, Note on the Conservative Action of Glaciers, *Proc. Roy. Geog. Soc.*, 10, pp. 785-787, 1888.

[5] See, for example, J. Brunhes, Érosion fluviale et érosion glaciaire, *Rev. de Géogr.*, 1, pp. 281-308, 1906-7; J. D. Kendall, The Formation of Rock Basins, *Geol. Mag.*, 83, pp. 164-174, 1926.

[6] W. M. Davis, *Die erklärende Beschreibung der Landformen*, pp. 411, 417, 1912.

[7] O. D. von Engeln, Phenomena Associated with Glacier Drainage and Wastage, *Zeits. f. Gletscherk.*, 6, pp. 104-150, 1911.

attributed to these submarginal streams it is localised near the terminal face of the glacier, and, moreover, it will almost certainly be obliterated by glacial erosion when the subglacial streams change their courses.

Only at the relatively low terminal face of a glacier that thins towards the terminus is melt-water collected into a trunk stream that is truly subglacial in that it flows over bedrock in an ice tunnel in the axis of the valley. Previously such water must have flowed in englacial streams—i.e. in tunnels within the ice—after having been swallowed by surface crevasses and moulins.

The Terminal Face and Glacier Snout

Some glaciers taper rapidly as they are wasted by melting to a thin snout or edge, while others end in cliffs. The cliffed margins of "tide-water" glaciers (Pl. XVI, 1, and Fig. 92), which enter fiords and "calve" to form icebergs, require no special explanation, as these glaciers have not been reduced much in thickness by ablation before reaching the sea. In cold polar regions some glaciers which end on land also have cliffed margins, however, which have been called by explorers "Chinese walls." These are glaciers of Ahlmann's "high-arctic" type (p. 131), which have interior temperatures (and basal temperatures also where the ice is thin) below the melting point of ice, and so are subject to ablation only at the surface and in the cliffs of the terminus.[8]

In contrast with these most "sub-arctic" glaciers—those in less cold regions, where the ice is at the melting temperature at least in summer and is therefore subject to rapid melting under the snout—have thin edges, at any rate where they are free to spread out laterally over level ground.[9]

Lateral moats are developed in some cases between valley sides and cliffed margins of valley glaciers especially where they are stagnant or have little movement. Such ice cliffs recede and are steepened as a result of radiation from the bare rock slopes of the valley sides when these are heated by the sun. Terminal and side cliffs bordering glaciers in the coldest parts of Greenland have been

[8] R. S. Tarr and O. D. von Engeln, Experimental Studies of Ice . . . , *Zeits. f. Gletscherk.*, 9, p. 122, 1915.

[9] Tarr and von Engeln, *loc. cit.* (8); A. R. Glen, A Sub-Arctic Glacier Cap: the West Ice of North-east Land, *Geog. Jour.*, 98, pp. 65-76, 1941.

ascribed also to the effects of marginal melting by solar radiation reaching them at a low angle.

Debris-laden lower layers contrasting with clean ice above, which may actually overhang at the edge, are characteristically present in Greenland glaciers. It has been pointed out by Chamberlin[10] that the edges of the discoloured (debris-laden) layers melt rapidly owing to their absorption of solar radiation; while at the same time the clean ice above is thrust forward over the lower layers. Odell[11] favours the view that the chief cause of cliff-development in these very cold glaciers is the more rapid movement of the clean ice over the lower debris-laden layers, which are more sluggish because of their load of debris.

Even the rapidly wasting thin snouts of glaciers in temperate latitudes end rather commonly in low cliffs (Pl. XVI, 2). In these glaciers a steep front may be caused by the arrival of a "wave" of ice due to a temporary thickening of the tongue following a high snowfall in the zone of alimentation some years earlier. Thus its presence may indicate that the glacier is extending down the valley for the time being, while a thin-edged condition may synchronise with a retreat of the ice front.

Glaciers which emerge from mountain valleys on to lowlands and are free then to spread out laterally with a feather edge or quite low marginal cliffs include "expanded-foot" glaciers and "piedmont" glaciers. The latter are formed where adjacent ice streams from upland valleys unite on a lowland to make a widespread relatively thin and sluggish sheet of ice. These are known at the present day in Alaska (Malaspina glacier) and in the Antarctic region. In the Glacial Period they were of common occurrence on mountain piedmonts in lower latitudes also.

Continental Glaciers

When glacier types are considered from the point of view of explaining the origin of landscape forms that date from the Glacial Period attention must be given to continental glaciers, more or less closely paralleled by the ice sheets of Greenland and Antarctica. Ice

[10] T. C. Chamberlin, Glacial Studies in Greenland, VI, *Jour. Geol.,* 3, p. 565, 1895.

[11] N. E. Odell, The Glaciers and Morphology of the Franz Josef Fjord Region, North-east Greenland, *Geog. Jour.,* 90, p. 116, 1937.

sheets (and ice caps) have no concave névé, but the collecting-grounds of snow are flat or very broadly convex, and normally no peaks or ridges project through them, though a few isolated rocky peaks, large or small, may project through any part of the ice sheet, more especially near the margins. These are termed "nunataks."[12] Around them crevasses open, which testify to glacial movement and indicate its direction.

Existing ice sheets vary in thickness up to perhaps 5,000 feet. Those of the Ice Age must have been considerably thicker in their central parts, but thinned out towards the margins, where peaks of moderate height stood out above them as nunataks. The gentle regional slopes on the flanks of these very broad domes of glacier ice were sufficient to induce centrifugal flow. In the marginal (low-latitude) regions the temperature of the ice must have been higher, and the mobility consequently greater, than in the ice sheets of the present day.[13]

On a lowland surface, an ice sheet may end in low cliffs of ablation, or, thrusting out to sea, may crumble into icebergs. An inland ice sheet may, on the other hand, overflow in rapidly-moving glacier tongues through gaps either in an enclosing mountain range, as in the Ross Sea sector of Antarctica, or in the edge of an upland or highland of small relief, as (formerly) in Norway.

The Glacier's Load of Rock Debris

One is accustomed to think of glaciers as streams of ice. Ice is indeed the flowing medium, but in some glaciers and some parts of other glaciers, notably in those of the eastern slopes of the New Zealand Alps (Pl. XVII, 1 and 2), ice is obviously little more than a cement which, like the cement in concrete, holds together an aggregate of stones. All gradations are found between such glaciers on the one hand, consisting of a conglomerate with an ice matrix, and those, on the other hand, consisting of almost pure ice contaminated only by a little blown dust that has been incorporated with the snows of the névé.

[12] Peaks and any bedrock prominences that project through névés are also termed "nunataks" (Pl. XI, 1).

[13] Much information regarding the dimensions of past and present continental glaciers is summarised by E. Antevs (*The Last Glaciation,* 1928).

From the point of view of explanatory geomorphology much interest attaches to the rock content of glaciers. An ice stream, like a water stream, is given its capacity for corrasion not by its movement alone but mainly by its "load," i.e. by the rock fragments which, equally with the water or ice, form part of the stream, and which the ice, in this case, uses as graving tools, thus "sculpturing" the landscape.

The sight of a glacier's superficial load of debris, to be regarded as a train of broken rock constantly in transit with the measurable and appreciable velocity of glaciers, will also convince the most sceptical observer of the ephemeral character of landscape forms—of the mountains, at any rate, from which the debris is in most cases obviously derived. It affords proof at least of the capacity of glaciers to transport already broken rock, though not necessarily to erode, for most if not all the visible debris on and in a valley glacier of the present day has fallen or streamed on to its surface after having been detached by physical weathering from the upper slopes and peaks of mountains. Indeed, this aspect of glacial transportation has fostered a school of "glacial protectionists" (Chapter XXII), who, being unconvinced of the ability of glaciers to erode, have regarded them as protecting the land surface beneath them while at the same time transporting over it the debris of disintegration of surrounding mountains. Without subscribing to this extreme doctrine one can readily agree that the evidence afforded by a rock-strewn glacier of the rapid wastage and destruction of mountains is indisputable.

That glaciers also erode (corrade) by a process of abrasion which can only be the result of their dragging rock fragments along in the bottom layer of ice and thereby grinding away not only the fragments themselves but the rock floor also is shown by the abundance of finely-powdered rock ("rock flour") in the melt-water, sufficient to give it always its characteristic "milky" appearance. So finely powdered is the rock flour in the rivers flowing from the Tasman and Godley glaciers (New Zealand) that sufficient remains in suspension to make the water still milky after it has passed through the long settling basins provided by the lakes Pukaki and Tekapo.

A general term for all rock debris incorporated in, in transit on or in, or carried and eventually deposited by glaciers is "moraine" or "moraines." Various kinds are distinguished. "Surface moraines" are superficial. Much rock debris that falls on to the surface (Pl. XVIII, 1) is buried by snow and by ice avalanches (Pl. XI, 2) from the valley sides in the upper and middles courses of a glacier, but reappears as "ablation moraine" in the region of ablation, becoming a more and more continuous layer, and perhaps completely hiding the glacier ice in the lower reaches where ablation has become rapid (Pls. XVIII, 2; LIII, 1).

Solar radiation is not reflected from moraines as it is from a clean ice surface, and surface rocks of moraines become strongly heated during periods of bright sunshine, but owing to the low thermal conductivity of rock material a layer of moraine affords protection from ablation. Small stones lying on a glacier, becoming heated, bore their way down and lie in pits; large stones, on the other hand, being too thick to conduct heat through them during the short period of sunshine while they shelter the ice beneath them from direct insolation, stand on pedestals of ice, forming "glacier tables."

Surface moraines are first formed as ridges ("lateral moraines") along the sides of the glacier, where valley-side debris falls on the ice. The ridges are irregular, being built of coalescing heaps of rock fragments, some of which may be of enormous size. Where two glaciers join forces their adjacent lateral moraines join forces also to form a ridge of moraine somewhere near the middle of the combined glacier, which is termed a "median moraine" (Pl. XII, 1). Median moraines, however, "are not confined to the surface as mere streaks of rocks, but extend to the very bottom of a glacier."[18a] "Englacial" debris is incorporated in the body of the ice, and that termed "subglacial" is dragged along under the glacier. Some moraines originally on the surface have become buried, as previously described, some debris falls or is washed by streams of surface water into crevasses, while some rock fragments also are plucked or scraped from the bottom and sides of a glacier trough. The latter method of collecting debris is the only one available in the case of

[18a] H. B. Washburn, Jr., The Harvard-Dartmouth Alaskan Expeditions, 1933-34, *Geog. Jour.*, 87, pp. 481-495, 1936.

a continental ice sheet except in the vicinity of rare nunataks. Chamberlin's observations on Greenland ice at the margin of a continental glacier indicate that in such cases the debris is concentrated in the bottom layer of ice.[14]

The plucking process, which supplies glaciers with the bulk of their coarse subglacial debris, is generally regarded as sharing equally with "scour", or abrasion, in the task of erosion under flowing ice.[15] "Pluck" becomes important whenever the ice may adhere by freezing of melt-water to projecting points of rock and drag them away with it. It is obviously most effective in the destruction and removal of jointed rock masses. Relief of pressure immediately in the lee of a projecting rock may be sufficient to raise the freezing point of the melt-water present above the existing temperature (which is nearly always in the vicinity of the freezing point), thus causing the formation of an ice film at the contact of glacier and rock, when adhesion and plucking follow. On the lee sides of larger projections of rock on the glacier bed ideal conditions for plucking occur, and in such situations abandoned glacier beds commonly have a quarried appearance.

It is sometimes convenient to extend the meaning of "plucking" to include "all those processes whereby debris is picked up and incorporated in the moving ice whether by frost pry, adhesion, or simply by inclusion of previously loosened materials."[16]

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[14] T. C. Chamberlin, Recent Glacial Studies in Greenland, *Bull. Geol. Soc. Am.*, 6, p. 215, 1895.

[15] A Penck, The Valleys and Lakes of the Alps, *Rep. VIII Internat. Geog. Congr.*, p. 177, Washington, 1905.

[16] M. Demorest, Glacial Movement and Erosion: a Criticism, *Am. Jour. Sci.*, 237, p. 602, 1939.

CHAPTER XII

Glacial Erosion; Glaciated Plains and Plateaux

Observations on existing glaciers make it clear that moving ice is effectively co-operating with other agents in the sculpture of landscape forms. The presence of abundant rock flour in the melt-water from mountain-and-valley glaciers, which gives it its characteristic "milkiness," testifies that vigorous abrasion of bedrock is going on beneath the ice (p. 144) and a heavy surface load of detritus of coarser grades is commonly carried also.[1] Though some observers of Alpine glaciers have regarded them as less efficient valley-cutters than equivalent water streams, others consider that though this may be true in a few instances of small, shrunken, and perhaps stagnant glaciers, a very different story must be told of large, actively moving glaciers and especially of the vast ice sheets and ice streams of the Glacial Period.

Apart from the question of quantitative efficiency in valley-cutting by corrasion, about which there may be room for some difference of opinion, there can be no doubt of the capacity of glaciers—even the smallest of them—to gnaw backward into uplands and mountains that stand above the ice level. Though admittedly the mechanism of this process is still somewhat mysterious, there can be no question of the efficiency and rapidity with which it works. It is the extension and enlargement of valley heads by this process, and quite possibly a similar attack on the steeper parts of valley floors, that undoubtedly supplies glaciers with a considerable proportion of the rock debris they carry. At the same time corrasion is in progress under the ice, and even the avalanching of rock waste from valley sides on to a glacier (Pl. XVIII, 1) testifies in many cases to the work the ice stream has done in steepening the side walls of its trough either by vertical or by lateral corrasion.

[1] This subject has been discussed by J. Geikie, *Earth Sculpture*, Ch. X, 1898.

Quantitative Efficiency of Glacial Corrasion

Not many confident expressions of opinion have been put on record by experienced observers as to the relative efficiency of glaciers and rivers as valley-makers. It is, therefore, of interest to note the conclusion of von Engeln that, where working side by side and carrying off the drainage from similar areas, glaciers are more efficient valley-making agents than rivers.[2] The dictum is based on comparison of glacier and river work observed side by side in Alaska. Tarr also, in the final statement of the results of his studies of Alaskan glaciers, pronounced on this point in no uncertain terms:

> The impressive volume of sediment, fine and coarse, which the glacial streams are transporting leads the inquiring mind to raise the question as to its origin. Streams having their sources in the rainfall are not often so sediment-laden as the glacial streams normally are; indeed even the exceptional land-supplied streams are rarely as heavily burdened even for a few days as the glacial torrents normally are for several months. Particularly is the question of the finer grained sediment of interest. It is abnormal in quantity as compared with mountain streams in general, and yet it comes from a drainage area largely protected by snow and ice against those atmospheric agencies which transform hard rock to fine clay. Can there be any doubt but that the glacier, which protects the rock against the atmospheric agencies, must attack it with equal or even greater vigour in order to obtain this vast burden of sediment that the streams bear away?[3]

Geomorphic Evidence of Glacial Corrasion

Ice sheets of the present day yield only fragmentary and tantalisingly inadequate information as to what is going on beneath them. More is to be gleaned by examination of surfaces formerly ice-covered and recently exposed. The contrast between the profiles of two islands lying off the coast of Greenland, one of which has and the other of which has not been overridden by an ice sheet, are shown in Fig. 45. The former has a smooth, "ice-shorn" surface,

[2] O. D. von Engeln, Phenomena Associated with Glacier Drainage and Wastage, *Zeits. f. Gletscherk.*, p. 142 (1911).

[3] R. S. Tarr, Glaciers and Glaciation of Alaska, *Science*, 25, pp. 241-258, 1912.

the presence of which implies not necessarily deep abrasion but at least the removal of asperities and minor forms of relief characteristic of erosive processes under the operation of which the now ice-shorn hill originated.

The chief factor determining strength of glacial abrasion is velocity of ice movement, but thickness (and consequent weight) of ice is of importance also. Commonly, moreover, the thickest parts of an ice sheet move most rapidly, and uniformly thin sheets

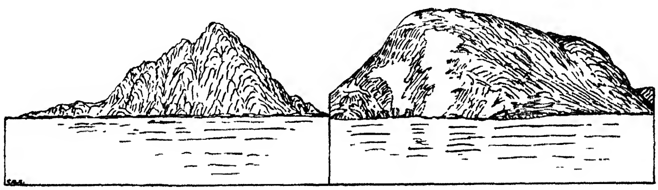

Fig. 45. Islands of similar rocks off the coast of Greenland. Left, Dalrymple Island, unglaciated; right, Cary Island which has been overswept by ice. (From photographs by T. C. Chamberlin, *Bull. Geol. Soc. Am.*, 6, Pl. 10, 1895.)

tend to be sluggish or stagnant. Thus over a land surface of small relief and little slope a continuous thin ice covering may be almost entirely protective, as is to be inferred from observations near the edges of ice-covered plateau areas bordering the Ross Sea, in Antarctica.[4] Here the snowfall is extremely small, and the ice sheet is thin and sluggish.

It is on record also that in East Sutherland, where the Scottish ice sheet of the Glacial Period was "probably thin and certainly sluggish," even a preglacially weathered surface of gneiss beneath it was not eroded by it. In this district common and widespread occurrence has been recorded of "glacial drift containing unweathered boulders resting upon undistorted weathered gneisses, so soft that they crumbled in the hand."[5] Under thin ice hard freezing of the ground has no doubt afforded protection from mechanical disturbance short of actual abrasion in some such cases.

Observations made in Norway at the margin of a modern ice cap indicate that where there is appreciable movement of the ice

[4] Griffith Taylor, Physiography and Glacial Geology of East Antarctica, *Geog. Jour.*, 44, pp. 365-82, 452-67, 553-71, 1914.

[5] E. B. Bailey, *Quart. Jour. Geol. Soc.*, 96, p. 257, 1940.

concentration of flow occurs along the lines of pre-existing furrows of the surface, causing them to be gouged out, thus somewhat strengthening a former weak relief.[6]

Surfaces of considerable relief, such as the northern end of the Mission Range, Montana,[7] which was overrun by the margin of the Canadian ice sheet, and the hills of the Island of Lewis, overridden by the Scottish ice,[8] have had all salient features modified by abrasion without suffering deep erosion anywhere. In Lewis,

> ridges have been smoothed down, escarpments bevelled off, and asperities in general softened, . . . abrasion and accumulation together having thus resulted in the production of a more or less undulating surface. In the phenomena of "crag and tail" we see another effect of the same twofold action. Isolated stacks and bastions of rock, which faced the direction of ice-flow, have been rounded and bevelled off, and frequently a hollow dug out in front, while morainic debris has been heaped up behind to form the so-called tail of the hill. . . . All well-glaciated areas show a somewhat monotonous outline —round-backed rocks, smoothed and undulating hill-slopes and hill-tops; in a word, undulating contours are everywhere conspicuous. (J. Geikie)

Roxen Lakes

Ice sheets thousands of feet thick, such as covered and moved over Canada and Scandinavia in the Glacial Period, certainly removed from pre-existing level upland and lowland surfaces of those regions all the weathered waste down to fresh bedrock, which was scored, scratched, and polished by the ice, or more correctly, by the rock fragments dragged along under the ice. The surface of even the most resistant rocks was differentially abraded to the extent of developing mammillated knolls and of excavating the confluent hollows in which lie the innumerable shallow lakes with integrated drainage systems still infantile in a postglacial cycle of normal erosion which characterise these regions; and some infaulted outliers of weaker formations have been converted by deeper, selective erosion

[6] O. D. von Engeln, Erosion Marginal to a Plateau Glacier, *Bull. Geol. Soc. Am.*, 46, pp. 985-998, 1935.

[7] W. M. Davis, The Mission Range, Montana; *Geog. Rev.*, 2, pp. 267-288, 1916.

[8] J. Geikie, On the Glacial Phenomena of the Long Island, or Outer Hebrides, *Quart. Jour. Geol. Soc.*, 29, pp. 532-545, 1873; *Earth Sculpture*, pp. 193-95, 1898.

into rock basins (Fig. 46). According to Davis's interpretation of the landscape forms of south-central Sweden that region presents examples of somewhat deep ice-sheet erosion selectively located on such areas of relatively weak stratified rock (Palaeozoic limestone) there surrounded by resistant crystalline rocks. On the latter terrain an upland plateau (peneplain) surface has been affected but little by glacial erosion. Rock-rimmed lake basins (for example, Lakes Roxen and Glan) have been thus formed by selective glacial erosion.

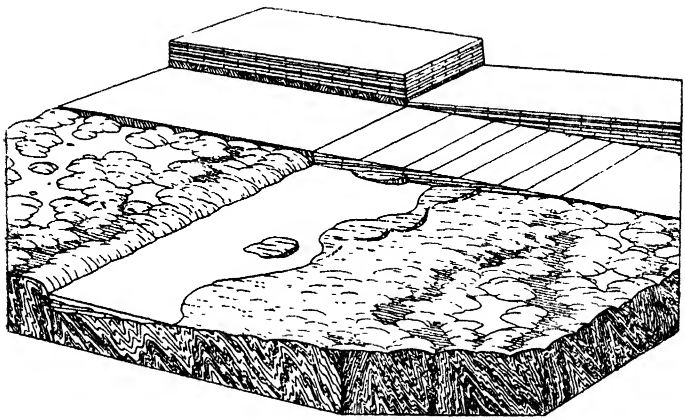

Fig. 46. Origin of lakes of the Laurentian upland of Canada. Centre, the "roxen lake" Timiskaming; right and left, lakes of the more ordinary Canadian kind occupying basins made up of many confluent hollows of the glaciated surface. (After W. M. Davis.)

These lakes lie in fault angles and are bounded on the one side by fault-line scarps (which have been interpreted by some other observers, however, as fault scarps). The Canadian lake Timiskaming is similar, and has been termed, therefore, a "roxen" lake (Fig. 46).[9]

The Question of Glacial "Peneplanation"

An estimate made by Helland, based on calculation of the volume of glacial debris carried southward by the northern ice sheet into central Europe, that the glaciated region of Sweden and Finland

[9] W. M. Davis, Notes on the Description of Land Forms, 10: Fault-line Scarps in Central Sweden, *Bull. Am. Geog. Soc.*, 45, pp. 518-520, 1913; A Roxen Lake in Canada, *Scott. Geog. Mag.*, 41, pp. 65-74, 1925.

which furnished this debris must have been lowered 255 feet by abrasion has been regarded by J. Geikie[10] as excessive, and he has suggested as a more conservative figure a third of this amount of lowering. There is little evidence, indeed, that abrasion of unweathered hard bedrock has ever been carried to a great depth on surfaces initially of small or moderate relief under even the thickest ice sheets, and no general support is given to statements that the existing small relief of the Laurentian peneplain,[11] for example, or the summit upland of northern Labrador,[12] is the result of the destruction of former mountains by glacial abrasion.

In spite of the efficiency sometimes ascribed to the plucking process as a provider of coarse subglacial rock debris (p. 146), it has even been suggested that some sheets of moving ice may erode vigorously only as long as they have the use of preglacially weathered debris as abrasive material[13] (see Chapter XXII). Locally, a patch of openly jointed and easily plucked hard rock may not only itself yield easily to glacial excavation, but may also keep up a supply of abrasive material which makes it possible for the ice to plough out a hollow under its lee by means of the scouring process.[14] Such an event will produce rather than destroy relief, however, and this argument is against rather than in favour of glacial planation.

Uplands of small or moderate relief may have been protected from deep abrasion and dissection at the climax of glacierisation, or ice flood, by the continuous ice sheets upon them and yet had their smooth surfaces broken or dissected, at least on their steeper slopes and on their flanks, owing to development of discontinuous glaciers after some amelioration of climate had taken place, or in a later epoch of less intense refrigeration, as has been observed, for example,

[10] J. Geikie, *Earth Sculpture,* pp. 191-192, 1898.

[11] Under the head "peneplains of ice erosion" in J. Park, *A Textbook of Geology,* 2nd ed., p. 51, London, 1925.

[12] N. E. Odell, The Mountains of Northern Labrador, *Geog. Jour.,* 82, p. 209, 1933.

[13] M. Demorest, Glaciation of the Upper Nugssuak Peninsula, W. Greenland, *Zeits. f. Gletscherk.,* 25, pp. 36-56, 1937.

[14] M. Demorest, Glacial Movement and Erosion: a Criticism, *Am. Jour. Sci.,* 237, p. 601, 1939.

in Norway.[15] Fluctuations of glacial intensity, or alternations of epochs of greater and less intensity of glaciation and of these with epochs of mild climate and normal erosion, introducing phases of oncoming and waning glacial conditions with consequent superposition of the features of one phase on those of another in palimpsest fashion, have allowed of many complications, including the combination of the effects of ice-sheet work (whether manifested as abrasion or protection) with the contrasted effects of back-wearing erosion ("sapping") at the heads and margins of small separate glaciers. Hobbs has pointed out that there has been, in a late phase of glaciation in Norway, a conservation of former low relief, and possibly a weakening of it by abrasion, under central parts of ice caps on blocks ("pedestals") between fiords, whereas at the steep margins of these, where the surface descends steeply into fiords, powerful abrasion in ice-outflow channels has deepened notches, between which residuals now stand up with strong relief[16] (Fig. 75).

The rocky "standflat" of the Norwegian low coastal strip, though it was ice-covered, seems not to have been levelled by glacial *abrasion,* whatever its actual origin may have been (Chapter XV).

Upland Grooving

There are instances of occasional glacial accentuation of relief beneath ice sheets, which has, though rather exceptionally, produced striking landscape effects. Only rarely, where the form and disposition of ice-buried valleys have especially favoured the process, has the gouging-out of deep grooves with the dimensions of large valleys or lake basins taken place under ice sheets in regions of small or very moderate relief (such as peneplains) whether low-lying or standing high. In the Finger Lakes district of northern New York (Cayuga, Seneca, and several other lakes) local concentration of ice-sheet flow occurred along the lines of pre-existing valleys of no great depth, resulting in not only the shaping of the valleys into grooves with U-shaped cross profile but also the local

[15] E. Richter, Geomorphologische Beobachtungen aus Norwegen, *Sitzungsb. Wiener Akad., Math. Naturw. Kl.,* 105 (1), pp. 152-164, 1896; W. M. Davis, Glacial Erosion in France, Switzerland, and Norway, *Proc. Boston Soc. Nat. Hist.,* 29, pp. 273-322, 1900 (reprinted in *Geographical Essays*); W. H. Hobbs, *Characteristics of Existing Glaciers,* p. 74, 1911.

[16] *Loc. cit.* (15), p. 76.

deepening of these to form the rock basins that contain the present-day lakes[17] (Fig. 47). By a combination of circumstances a considerable flow of ice was here concentrated along definite lines. The concentration was localised in suitably placed valleys in an area of moderately strong relief situated at a preglacial divide up and over which the southward-moving ice of the continental glacier had to take its course. A number of parallel valleys were present aligned in the general direction of flow but opening to the north, and the southward-moving ice which crossed the divide "was thrust into channels that narrowed progressively southward . . . The effect

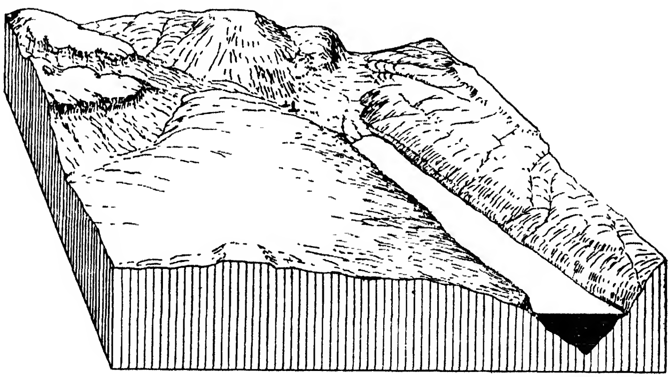

Fig. 47. The southern end of Cayuga Lake, New York, lying in a basin of glacial excavation gouged out beneath the ice sheet of the Glacial Period. The direction of ice movement was, at this point, uphill and along the groove which continues the line of the lake basin. (After von Engeln, redrawn.)

was to accommodate the excess of volume by increase in the rate of flow until the effects of erosion magnified by the faster motion had deepened the passageways enough to provide the enlarged cross section necessary for an unimpeded, uniform forward motion of the glacier." This deepening of the channels converted the valleys into the rock-rimmed basins now the Finger Lakes. They "are deepest in the narrowest parts of the preglacial valleys." The total depth of the grooves is relatively small as compared with the average thickness of this part of the continental glacier, which was about 3,000 feet. (The quoted passages are from von Engeln.)

[17] R. S. Tarr, Lake Cayuga as a Rock Basin, *Bull. Geol. Soc. Am.*, 5, pp. 339-356, 1894.

"The overdeepening of the north-south valleys left the tributary east-west valleys hanging at their junctions with the main valleys—a relation that has permitted the postglacial development of innumerable waterfalls and gorges at the lower ends of the tributary valleys."[18]

Contrasting with such deep groovings as those of the Finger Lakes a more general slight accentuation of relief has been observed on adjacent parts of the same upland. In the valley shown in Plate XIX, 1, for example, it appears that a preglacial divide has been eliminated where a stream of the bottom ice of the continental glacier has cut a groove through a col. The landscape has become a "grooved upland" in the sense in which the expression is understood by von Engeln (not of Hobbs).[19]

It has been suggested in explanation of the excavation of valley grooves beneath ice on this plateau that under rapidly moving very cold ice so much heat is abstracted from the underlying rocks that the level of the isogeotherm of the pressure-determined melting-point of ice descends below the rock surface, so that the floor may be disintegrated to some depth by the freezing of ground water in crevices, thus providing debris for removal by the ice. The deeper the ice the greater perhaps will be the effect, and so infraglacial valleys may be deepened.[20]

Another example of a grooved upland is found on the peneplain of the high south-western interior of Norway, which after being uplifted suffered abrasion under the Scandinavian ice sheet of the Glacial Period.[21] The relief of the surface amounts to several hundred feet, and this is in part the result of glacial groove-cutting. The grooves are very broadly U-shaped with rather steep sides and are disposed radially in relation to local centres of ice dispersal, as is indicated by the position of the Hardanger ice cap, or plateau glacier, a present-day vestige of the ice sheet, which may be taken

[18] O. D. von Engeln, in "The Palaeozoic Stratigraphy of New York" by various authors, *XVI Internat. Geol. Congr.* (1933), Guidebook 4, p. 54, 1932. The theory of glacial erosion of the basins of the Finger Lakes is categorically denied by H. L. Fairchild, Geological Romance of the Finger Lakes, *Smithsonian Rep. for 1927,* pp. 289-298, 1928.

[19] O. D. von Engeln, *loc. cit.* (6); W. H. Hobbs, *loc. cit.* (15), p. 30.

[20] C. D. Holmes, Glacial Erosion in a Dissected Plateau, *Am. Jour. Sci.,* 33, pp. 217-232, 1937.

[21] O. D. von Engeln, *loc. cit.* (6).

as an indication that they really owe their origin or deepening to ice work. They appear to follow any suitably disposed shallow preglacial valleys, which have guided the more rapidly moving threads of glacier flow. In the grooving of the upland every preglacial depression, however slight, appears to have influenced the direction of flow of the bottom ice. "Minor high-level hollows were only smoothed, straightened, and slightly deepened; larger, more continuous ones were excavated to become conspicuous grooves" (VON ENGELN). These shallow groovings of the upland plateau contrast strongly with relatively infrequent deep troughs (in part fiords on the west and piedmont lakes on the east), which were incised thousands of feet below the upland surface by ice streams concentrated, according to competent opinion,[22] along the lines of preglacial valleys already deeply incised on the margin of the plateau by normal rejuvenation, and even widened out in their lower parts, before the Ice Age. Initial grooves, if present aligned in the general direction of ice movement, need be only of sufficient depth, however, to give the ice above them a greater rapidity of flow than the average to insure that further deepening of the grooves will take place, if there is any basis of truth in Nansen's formula which states that "the erosive power of a moving glacier may increase approximately with the third power of the velocity of the motion at its under side."[23]

Intermediate in character between the features of the grooved upland and the deeply-cut fiords and fiord-like troughs, but of similar origin to the latter, are shallower but relatively broad U-shaped valleys, with cross profiles approximating to a catenary curve, which are of common occurrence intersecting the relatively low grooved upland of northern Norway (in the Tromsö district, for example) and also in Scotland (Pl. XIX, 2), where the preglacial relief was considerable but the depth of scouring generally less profound.

[22] H. W. Ahlmann, Geomorphological Studies in Norway, *Geog. Ann.*, 1, pp. 1-148, 193-252, Stockholm, 1919; Ahlmann and Laurell, Repräsentative Beispiele . . . , *Cong. Internat. Géog. Amsterdam*, 2, p. 5, 1938.

[23] F. Nansen, Strandflat and Isostasy, *Vidensk. Skrifter, M.-N. Kl., 1921,* 11, p. 21, 1922.

CHAPTER XIII

Glaciated Mountains

APART FROM THE deeper groovings which result from corrasion and find expression in fiords and valleys of related form, the most striking and conspicuous landscape features developed in relation to mountain-and-valley glaciers are found in the corries, arêtes, and pyramidal-sharpened peaks on and among mountains that have not been completely overridden but have stood out above an ice flood as nunataks and divides between adjacent névés and valley glaciers.

Similar features modifying, or superimposed on and mingled with, those resulting from widespread glacial abrasion have been developed in regions from which a continuous ice sheet or an almost continuous net of glaciers has partly melted away, exposing salient and steep landforms to erosion of a new kind; or they have made their appearance among mountains so situated that they have nourished only small and discontinuous glaciers.

GLACIAL CONTRASTED WITH NORMAL LANDSCAPES

In glaciated mountain regions the contrast between normal landscape features ("normal" being here used strictly in the geomorphic sense) and those modified or transformed by glacial erosion is noted particularly by newcomers. Observers who are Alpine dwellers have come to regard glaciated landscapes in which there is a combination and association of glaciated forms with those developed by rain and rivers as perfectly natural, and so fail to distinguish as such the characteristically glaciated forms.[1]

[1] Not only the Alpine dweller but the visitor also whose eye has become accustomed to Alpine scenery may be under this spell. (See, for example, E. J. Garwood, Features of Alpine Scenery due to Glacial Protection, *Geog. Jour.*, 36, pp. 310-339, 1910; T. G. Bonney, *The Work of Rain and Rivers*, Cambridge, 1912; J. W. Gregory, *The Nature and Origin of Fiords*, pp. 425-432, 447, London, 1913.) Owing to the same failure to make a just distinction Alpine geomorphologists have claimed also as typical products of ice erosion forms which (according to E. de Martonne) are due in great part to river work and have been only modified by ice (Quelques données nouvelles sur la jeunesse du relief préglaciaire dans les Alpes, *Rec. Trav. offerts à J. Cvijić*, pp. 121-140, Belgrade, 1924).

The weird and striking contrast may, however, astonish an observer whose eye has been trained in the field of normal erosion. The impressions of Willard D. Johnson when he visited the High Sierra district of the Californian Sierra Nevada in 1883 have been recorded by him as follows:

> I was a maker of topographic maps, of some experience, and had a topographer's familiarity with the erosion aspects of mountains. I had as well, however, something of the inquisitiveness of the physiographer as to the origin and development of topographic forms.
>
> The first station occupied in this work of survey was Mount Lyell, one of the most widely commanding summits of the vast mountainous tract of the High Sierra.
>
> From Lyell there was disclosed a scheme of degradation for which I had not been in the least prepared. No accepted theory of erosion, glacial or other, explained either its ground-plan outlines or its canyon-valley profiles; and, so far as I can see, none makes intelligible its distinctive features now. The canyons, at their heads, were abnormally deep; they were broadly flat-bottomed rather than U-formed, the ratio of bottom width to depth often being several to one; and their head walls, as a rule, stood as nearly upright, apparently, as scaling of the rock would permit. I characterised them, figuratively, as "down at the heel." In many instances the basin floor, of naked, sound rock in large part, and showing a glistening polish on wet surfaces, was virtually without grade, its drainage an assemblage of shallow pools in disorderly connection; and not infrequently the grade was backward, a half-moon lake lying visibly deep against the curving talus of the head wall, and visibly shallowing forward upon the bare rock floor.
>
> The amphitheatre bottom terminated forward in either a cross cliff or a cascade stairway, descending, between high walls, to yet another flat. In this manner, in steps from flat to flat, commonly enough to be characteristic, the canyon made descent. In height, however, the initial cross cliff at the head dominated all. The tread of the steps in the long stairway, as far as the eye could follow, greatly lengthened in down-canyon order. In that order also the phenomena of the faintly reversed grade and of the rock-basin lakes rapidly failed. Apparently, at the canyon head the last touch of vanishing

glaciation had been so recent that filling had not been initiated, while downstream incision of the step cliffs and aggradation of the flats had made at least a beginning in the immense task of grade adjustment; the tread of the step was graded forward, but so insensibly as a rule that its draining stream lingered in meanders on a strip of meadow, as though approaching base-level. These deep-sunk ribbon meadows, still thousands of feet above the sea and miles in length, reflecting in placid waters their bordering walls or abnormally steep slopes, presented an anomaly of the longitudinal profile in erosion no less impressive than that of the upright canyon heads.

In ground plan the canyon heads crowded upon the summit upland, frequently intersecting. They scalloped its borders, producing remnantal-table effects. In plan, as in profile, the inset arcs of the amphitheatres were vigorously suggestive of basal sapping and recession. The summit upland—the preglacial summit upland beyond a doubt—was recognisable only in patches, long and narrow and irregular in plan, detached and variously disposed as to orientation, but always in sharp tabular relief and always scalloped. I likened it then, and by way of illustration I can best do so now, to the irregular remnants of a sheet of dough on the biscuit board after the biscuit tin has done its work.

In large part, apparently, a preglacial summit topography had been channeled away. By sapping at low levels, by retrogressive undercutting on the part of individual ice streams at their amphitheatre heads in opposing disorderly ranks, the old surface had been consumed, leaving sinking ridges, meandering dulled divides, low cols or passes, and passageways of transection pointing to piracy and to wide shiftings of the glacial drainage. There was not wanting a scattering of the more evanescent sharp forms of transition which the hypothesis would require, as thin arêtes, small isolated table caps, needle-pointed Matterhorn pyramids with incurving slopes, and subdued spires (in the massive granite tracts) with radiating spurs inclosing basin lakes. The broader areas of this deep erosion, where complex channeling seemingly had passed into the phase of confluent glaciation, presented a much less intelligible ground-plan pattern. In every case, however, there was still an approximately central draining

canyon. It was the sprawling high-walled masses of the residual uplands that told a clear story.

The legitimate inference was that the suspension of glaciation had suspended as well a process which had threatened truncation of the range. It was obvious, postulating recession, that the canyons of this summit region were independent in their courses, and had developed independently, of the initial upland drainage plan. It was clear from their grade profiles that they were not stream-cut. The inference was not only legitimate, but necessitated, that, profoundly deep as they were, they were essentially of glacial excavation.[2]

Cirques, Troughs, and Steps

In more prosaic terms the detail features found so astonishing by Johnson may be sorted out as (1) *cirques* (Pl. XX, 1), (2) broad-floored and steep-sided (trough-shaped) valleys with down-stepping profiles (Chapter XIX), and (3) numerous lakes, the presence of

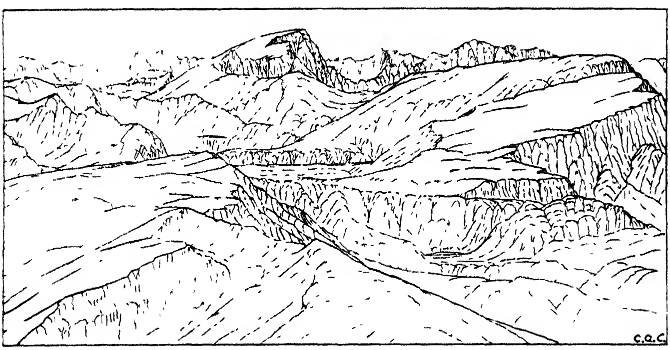

Fig. 48. Smooth upland remnants encroached on by cirques, Sierra Nevada of California, with Mt. Whitney in centre. (Drawn from a photograph.)

which indicates reverse slopes on the rock floors of cirques and steps (Pl. XX, 2; see also Chapter XIX). This glacial ensemble has to some extent replaced a normal subdued upland surface (Figs. 48, 49); and for this surface where it has been destroyed sharp-edged arêtes and pointed horns have been substituted—forms which result

[2] Willard D. Johnson, The Profile of Maturity in Alpine Glacial Erosion, *Jour. Geol.*, 12, pp. 569-578, 1904.

from intersection of the precipitous walls of valley-head and other cirques, or glacial amphitheatres (Pl. XX, 1 and 2).

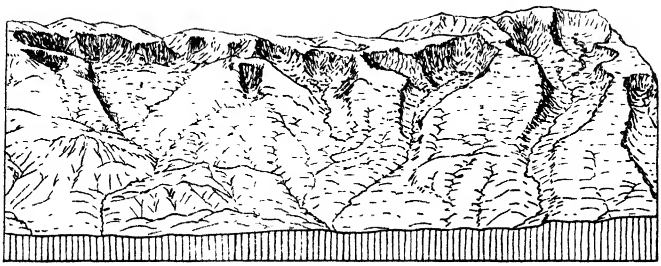

Fig. 49. Upland scalloped by glacial sculpture, north flank of Uinta Mountains. (Redrawn after a diagram by W. H. Bradley, U.S. Geol. Survey.)

Hanging Valleys

Another feature, which did not catch the eye of Johnson so much as the scalloped and "fretted"[3] upland (Pl. XXI, 1 and 2) in the landscape as seen from his lofty viewpoint, but which obtrudes itself on the attention of a novice who happens to be a valley climber rather than an Alpinist, is the ubiquitous "hanging" valley (Pls. XXII, 1 and 2). The side streams (the water streams of the postglacial cycle of normal erosion just initiated) practically never join the main stream in a glaciated trough at grade. The junctions of the valleys from which they emerge into the main valley are on the contrary highly discordant, so that the water streams of to-day either plunge as falls from the lips of well-defined side valleys that open at great heights above the floor of the main or have cut as yet only insignificant notches in such lips (Pl. XXIII, 1 and 2). Whether all the hanging valleys that open into glaciated troughs have or have not originated in quite the same way, which is a question for later discussion, the assumption of their hanging attitude is in most cases rather obviously related to the development of a glacial trough form in the main valley.

Related also to the preponderance of the trough form in glaciated valleys is an absence of valley-side spurs. As the windings of the floor of a normal valley are associated with interlockings of spurs

[3] So called by W. H. Hobbs, *Characteristics of Existing Glaciers,* p. 30, New York; 1911.

descending from opposite sides, it follows that valley-floor windings or valley curves of small radius are typically absent from glacial troughs. It is incorrect to describe such valleys as straight, however, for they quite commonly swing around through considerable angles on curves of wide radius (Pl. XXXVII, 2).

Lakes and Fiords

Piedmont lakes and fiords are characteristic features also of glaciated mountain regions, the former where great valley glaciers have descended to or almost to a lowland in front of the mountains, and the latter where they have descended to the sea. These closely related lakes and fiords (Pl. XXII, 2), elongated, very deep, with steep and spurless walls, without embayments and rarely branching, but bordered at the sides by hanging valleys, lie in typically glaciated trough valleys (Figs. 49A, 120, 124), which exhibit not only the features just enumerated but also other familiar evidences of glacier occupation such as grooved and polished rock walls and deposits of morainic debris on such parts of the floors as are not submerged. The floors of true fiords and of piedmont lakes have been vertically excavated so that they have the form of rock-rimmed basins, the origin of which will be discussed more fully in Chapter XX. Innumerable smaller lakes which lie also in rock basins testify equally well to the ability of thick ice streams to excavate differentially the rock floors over which they pass.

Processes of Glacial Erosion

The products of two distinct processes, to be regarded as separate phases of glacial erosion combined in very variable proportions, are to be found among the features enumerated above as characteristic of glacially-sculptured mountains. These are vertical corrasion and the "sapping" process that steepens precipices. The former is a well recognised process, though there is room for much difference of opinion as to whether its rôle is dominant or relatively insignificant in glacial sculpture. The way in which thin Alpine glaciers appear to deposit moraine beneath them and override it has convinced some observers that corrasion is possible only under thick and rapidly moving ice streams, but, on the other hand, many glaciers of quite small dimensions yield milky or turbid

melt-water, which must be taken to indicate that "scour" is actively in progress under them.

Glacial Corrasion

The origin of typical U-shaped or trough-shaped glacial valleys has been ascribed by Penck to the cutting by vertical corrasion of a trench well below the floor of the preglacial valley, a process which he terms "overdeepening".[4] This is a clarification of the "ice-plough" idea of older glaciologists. Such overdeepening involves "oversteepening" of valley sides. The trench or groove ploughed out by the glacier will vary in depth in different parts owing to varying glacier volume and available width of valley. De Martonne would recognise as "true" overdeepening only that which lowers the valley floor below a theoretical normal "profile of equilibrium", as, for example, in the excavation of the basins of piedmont lakes[5] (Fig. 50).

Glacial corrasion is necessarily a subglacial process. It affects, however, not only the floors of valleys occupied by glacier tongues, which are situated commonly below the snow-line, but also those of high-perched cirques at valley heads and of the cirque niches that hold hanging glaciers, as is indicated by the later exposure of well-polished surfaces of bare rock on these floors and by the presence on them of rock-rimmed hollows now occupied by lakes and tarns. In typically glaciated mountain regions, however, peaks and ridges have stood out prominently above the névés and glacier tongues even of the "ice floods" of the Glacial Period, and the summits of these "nunataks" have necessarily been immune from glacial corrasion.

Upper valley sides and even summits and ridge crests may have slopes comparatively gentle when considered in relation to the steep sides of inner troughs which comparatively recently have been, and perhaps still are, occupied by trunk glaciers (Fig. 127). Though physical weathering undoubtedly is and has been very active on exposed peaks there are good reasons for rejecting the contention of the "glacial protectionist" school (Chapter XXII)

[4] A. Penck, Die Uebertiefung der Alpentäler, *VII Internat. Geog. Congr.*, 2, pp. 232-240, 1900; Glacial Features in the Surface of the Alps, *Jour. Geol.*, 13, pp. 1-19, 1905.

[5] E. de Martonne, *Traité de géographie physique*, Vol. 2, 5th ed., p. 911, 1935.

that *all* moderate upper slopes have resulted from the crumbling away of steeper, sharper forms above ice-level, while inner valleys have had their preglacial forms preserved by protective glaciers present in them. It seems safe, moreover, to adopt without discussion the view that *some* of the more subdued at least of the upland and summit forms are relics of a preglacial landscape of normal erosion on which the "biscuit-cutting" process described by Johnson (p. 159) and probably also deep groove-cutting by valley glaciers have done the work of partial destruction. Even this is not the whole story, however. Not all glaciated landscapes contain relics of initial forms; some, in the cores of high mountain ranges especially, present an appearance of "maturity"—to use a term borrowed from the cycle of normal erosion—that is, of thorough dissection (Pl. XXXVII, 2); but more commonly there are pronounced valley-side shoulders which separate upland or highland benches from lower slopes that lead steeply down to the floors of trough valleys. Not one only but several shoulders, separated by concave profiles, are sometimes present, indeed, the explanation of which makes a difficult problem and affords room for differences of opinion among geomorphologists (Chapter XXI).

A Cycle of Glacial Erosion?

Since glacial erosion and transportation dispose of vast quantities of rock, their continued operation implies considerable lowering of the land surface; and it appears that cirque erosion together with corrasion by valley glaciers would eventually destroy mountains, reducing them to lowlands.[6] In spite of some contrary statements, however (p. 152), no glacially-planed surfaces analogous to the peneplains that have resulted from the destruction of mountains by normal erosion have been recognised with certainty, perhaps because glacial conditions have generally been brought to a close by amelioration of climate before such a stage in a glacial geomorphic cycle has been attained. Even on the slopes of the Royal Society Range in Antarctica, a region still in the grip of intense refrigeration, a combination of conditions has apparently so slowed down some

[6] A "cycle of glacial denudation" has been deduced by W. M. Davis, Glacial Erosion in France, Switzerland, and Norway, *Geographical Essays*, pp. 658-666, 1909.

at least of the processes of glacial erosion that the cycle is not very far advanced. The hypothetical old-age landscape form which will be developed by glaciation when strong relief is eventually destroyed may be assumed to be not level, nor yet characterised by the very weak gradients of a normal peneplain, but accidented by a small-scale relief of irregularly scattered, steep-sided knobs or prominences of fresh rock, as is the case on some lowlands that are known to have been overswept and abraded by ice—the partly drowned "strandflat" of the Norwegian coastal fringe (Chapter XV) and the similar coastal lowland of Alaska, for example. "It is inferred that the end stage of a glacial cycle . . . will be a roches moutonnées field";[7] and it is so represented in a hypothetical last (or penultimate) stage of mountain destruction in a well-known diagram by W. M. Davis (see Fig. 63). It goes without saying that this form would differ from a normal peneplain also in being without a cover of waste weathered in place; and a still more important distinction would be absence of control by any base-level.

A lack of base-level control is already obvious in the mature stage of glacial erosion, and there is also absence of any systematic grading of valley profiles or land slopes. It may be urged that at the height of an ice flood the surfaces of ice streams may appear well graded both in trunk glaciers and also in secondaries, which moreover, may join a trunk at grade, or "accordantly", and that in a normal landscape also it is in reality the surfaces of water streams that are graded and join accordantly and not their beds;[8] but this argument gives little help in classifying valley profiles from which glaciers have melted away as mature or young. By using the same criteria that may be applied in the case of the normal landscape cycle, however, it is sometimes helpful to recognise "young", "submature", and "fully mature" stages of dissection and landscape development. Thus, Northern Labrador (Fig. 49A) is described as exhibiting "all stages from youth to maturity".[9] The transition from young to mature summit dissection as a mountain centre

[7] O. D. von Engeln, Glacial Geomorphology and Glacier Motion, *Am. Jour. Sci.*, 35, pp. 426-440, 1938.

[8] H. Gannett, Lake Chelan, *Nat. Geog. Mag.*, 9, pp. 417-428, 1898; W. M. Davis, *loc. cit.* (6), p. 657; A. Penck, *loc. cit.* (4), p. 239, 1900; G. K. Gilbert, Glaciers, *Harriman Alaska Exped.*, 3, p. 115, 1903.

[9] N. E. Odell, The Mountains of Northern Labrador, *Geog. Jour.*, 82, p. 209, 1933.

of glaciation is approached—where glaciation has been most intense —is shown at the right in the diagram by W. M. Davis reproduced as Fig. 90, p. 228.

In the development of the theory of the normal cycle of erosion it is usual to regard valley forms as running through a cycle parallel but not generally in step with the landscape cycle. So also, in discussing the possible adaptation of the cycle concept to glacial features, de Martonne[10] finds it convenient to consider separately the

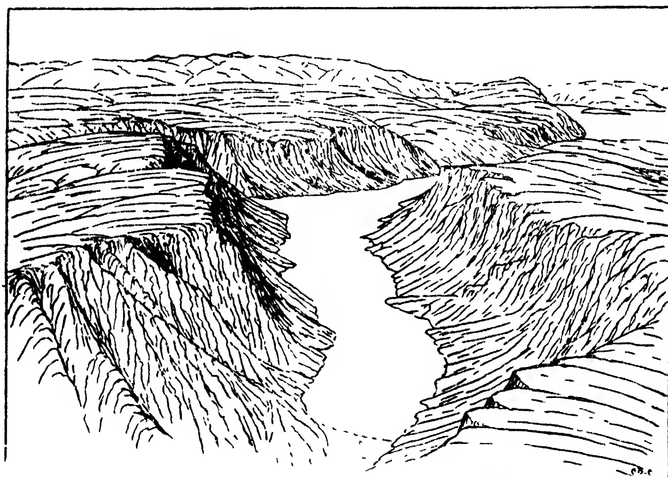

Fig. 49A. Young glacial dissection of an upland surface of small relief, Saglek Fiord, Northern Labrador. (Drawn from a photograph.)

distinct processes of cirque and valley erosion. It is in cirque development particularly that, as suggested in an earlier paragraph, stages of destruction of the initial landscape can be readily separated as young, submature, and fully mature. There must be a tendency eventually for cirques to coalesce to form "platforms of cirques",[11] arêtes between which have been eliminated by sapping, but such platforms must be of local development, and the lack of co-ordination by general base-level control must generally prevent wide planation by this process.

As regards valley forms, analogy with river work also suggests that the stage of youth will be brought to a close by an approach

[10] E. de Martonne, *loc. cit.* (5), p. 928.
[11] E. de Martonne, *loc. cit.* (5).

to grading, accompanied by a shaping of the trough to accommodate a glacier with the form of cross section best adapted to its flow. This cross section is bounded below, according to the theory of de Martonne,[12] by an arc of a circle. The longitudinal profile of the rock floor will remain, on the other hand, very uneven in detail, retaining reverse slopes and steps, but its generalised average slope may become somewhat regular (Fig. 50). When such a generalised

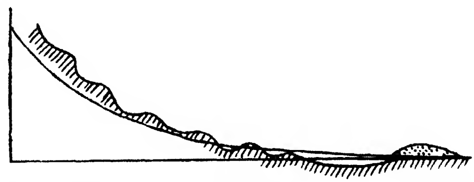

Fig. 50. Generalised graded profile of the floor of a mature glacier trough compared with that of an equivalent river. (After E. de Martonne.)

graded glacial profile ("profile of equilibrium") is attained it will be steeper than a theoretical normal profile of equilibrium (presumably the first continuously-graded profile that would be developed by an equivalent water stream on the same landscape). "True" overdeepening (as compared with this profile—Fig. 50) will not be present, according to the concept of glacial corrasion favoured by de Martonne, except in the lower valleys of long trunk glaciers near the terminal face of the ice; though under prolonged glaciation, which modifies the first graded profile, it may extend up the valley of the trunk glacier, but perhaps not into those of secondaries.[13]

"Initial" (Preglacial) Landscapes

The initial form for a cycle, or episode, of glacial erosion is generally, and probably quite correctly, assumed to be a normal landscape exhibiting the landscape forms of a cycle abruptly terminated by a climatic "accident".[14] In Alpine regions the forms were mature, or perhaps of multi-cycle origin; and under parts of the Scandinavian and North American ice sheets a former pene-

[12] *Loc. cit.* (5); also *loc. cit.* (1), p. 135.

[13] E. de Martonne, *loc. cit.* (5).

[14] "A complicated problem, involving many variables; for it is evident that the existing forms of glaciated mountains must vary not only with the competence or incompetence of glaciers to erode, but also with the stage of development reached in preglacial time, [etc.]" (W. M. Davis, *Appalachia,* 10, p. 395, 1905).

plain was buried, low-lying in some parts and high-standing in others, the latter in part rejuvenated by the cutting of valleys of considerable depth just anterior to the Glacial Period, which guided the deep incision of marginal fiords and fiord-like troughs by ice streams. One may enquire, however, whether a cycle of glacial erosion has ever been initiated by earth movements instead of a climatic accident, and it may be suggested that some parts of the polar regions may afford examples of this case, since it is possible that glacial conditions have prevailed there longer than elsewhere. According to the view expressed by Griffith Taylor[15] the Antarctic peneplain (or featureless surface of unknown origin) may have been converted by large-scale uplifts accompanied by block faulting into the Royal Society Range with its imposing scarped front during the world-wide end-of-Tertiary orogeny. If the climate of the region was then too cold for normal erosion a cycle of glacial erosion must thus have been initiated on the margin of the scarped plateau and in particular on the scarps, which were too steep for glacial protection under nearly stagnant ice.

[15] Griffith Taylor, Physiography and Glacial Geology of East Antarctica, *Geog. Jour.*, 44, pp. 365-382, 452-467, 553-571, 1914.

CHAPTER XIV

Glacial Cirques

THE TERM "cirque" is applied equally to valley-head amphitheatres (which, however, may be quite conveniently distinguished as "valley-head cirques") and to similar forms which are not distally prolonged as glaciated trough valleys, but perch either on the sides of glaciated valleys or on hills or mountain-sides not otherwise scarred or marred by glacial sculpture. These latter are sometimes referred to as "corries," but the distinction is not strictly made. They obviously have been occupied by short or hanging glaciers and bear the same relation to valley-head cirques as do hanging glaciers to névés that are extended down-valley as glacier tongues. Valley-head cirques also are sometimes termed corries, and the term corrie has been used as though meaning a small cirque; while yet another practice is to name only the hanging forms cirques, excluding valley-head amphitheatres from the category, the Scottish "corrie," Welsh "cwm," and German "Kar" being cited as synonyms.[1] In some European usage only the large and more symmetrical features, generally with hollowed-out floors that become lake basins, are termed cirques, and the homologous but generally smaller, less regular, and sloping-floored cirque forms in high-mountain areas that have become maturely dissected by glacial erosion are excluded.[2]

UPLAND SCULPTURE

Of all the processes of glacial erosion cirque enlargement by "sapping" has produced the most conspicuous and characteristic

[1] E. de Martonne, *Traité de géographie physique,* Vol. 2, 5th ed., p. 900, 1935. This author has, however, termed valley-head amphitheatres, "cirques" also (cf. *Ann. de Géog.,* 19, p. 314, 1910). By proposing to term amphitheatre valley heads of non-glacial origin "pseudo-cirques" O. W. Freeman (The Origin of Swimming Woman Canyon . . . , *Jour. Geol.,* 23, pp. 75-79, 1925) has recognised the use of the unqualified term "cirque" for glacial valley heads as established.

[2] Those with hollowed-out floors that contain lakes have also been distinguished by A. Penck as "closed" corries (cirques); others are "open". (Glacial Features in the Surface of the Alps, *Jour. Geol.,* 13, pp. 1-19, 1905.)

landscape features of glaciated mountains, more especially perhaps in the "young" stage of a glacial "cycle," while progressive destruction and replacement of preglacial features of the landscape have been in progress. The contrast between steep cirque walls and preglacial slopes is seen to best advantage in moderately and even strongly glaciated mountains that have entered on the glacial cycle with subdued summit forms. This is the contrast which Willard Johnson found so convincing in the Sierra Nevada (Chapter XIII), and which has been noted particularly in all those lightly glaciated

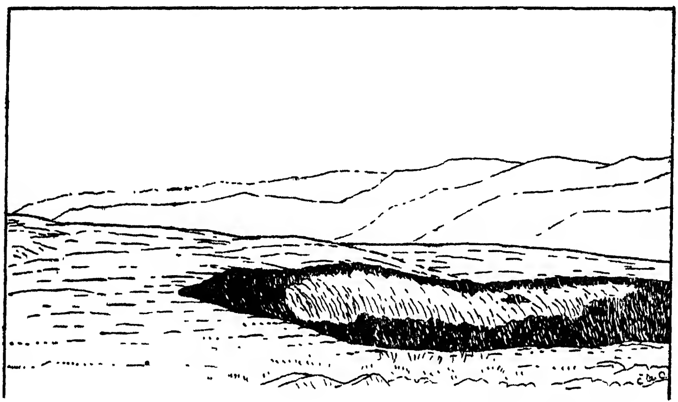

Fig. 51. "The Pocket," a glacial cirque interrupting a preglacial upland on Quadrant Mountain, Yellowstone National Park. (Drawn from a photograph by W. H. Hobbs.)

ranges of the American West that have on their summits areas and remnants of ancient erosion surfaces of small relief—for example, in the Big Horn[3] and Uinta[4] Mountains and on the uplands of the Yellowstone National Park[5] (Fig. 51). Subdued summit forms that are more strongly convex show the contrast almost equally well (Fig. 52). In this case there is produced a simple example of intersection of convex and concave surfaces.

[3] F. E. Matthes, Glacial Sculpture of the Big Horn Mountains, *U.S. Geol. Surv. 21st Ann. Rep.*, pp. 167-90, 1900.

[4] W. W. Atwood, Glaciation of the Uinta and Wasatch Mountains, *U.S. Geol. Surv. Prof. Paper 61*, 1909; W. H. Bradley, Geomorphology of the North Flank of the Uinta Mountains, *U.S. Geol. Surv. Prof. Paper 185*, pp. 163-99, 1936.

[5] W. H. Hobbs, *Characteristics of Existing Glaciers*, p. 27, 1911.

The convexly rounded summits of the mountains of North Wales have been described as subdued preglacial forms of normal erosion.[6] Glaciers of considerable size, heading in cirques, have

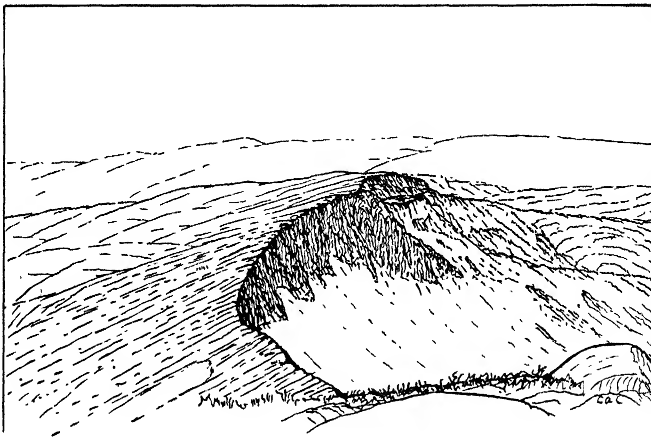

Fig. 52. View westward from Mt. Hoffman, Sierra Nevada of California. (From a photograph by A. C. Lawson, in G. K. Gilbert, *Jour. Geol.*, 12, 1904.)

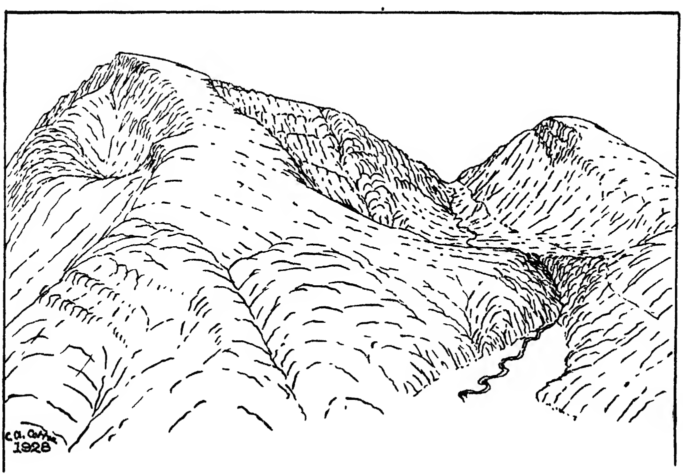

Fig. 53. Maes Cwm, between Moel Cynghorion and Foel Goch, Snowdon.

[6] W. M. Davis, The Systematic Description of Land Forms, *Geog. Jour.*, 34, pp. 308-9, 1909; Glacial Erosion in North Wales, *Quart. Jour. Geol. Soc.*, 65, pp. 281-350, 1909.

gnawed back into these round summits without destroying them (Fig. 53). Similar cirques, some of them of magnificent dimensions, are present also on Helvellyn and other mountains of the Lake

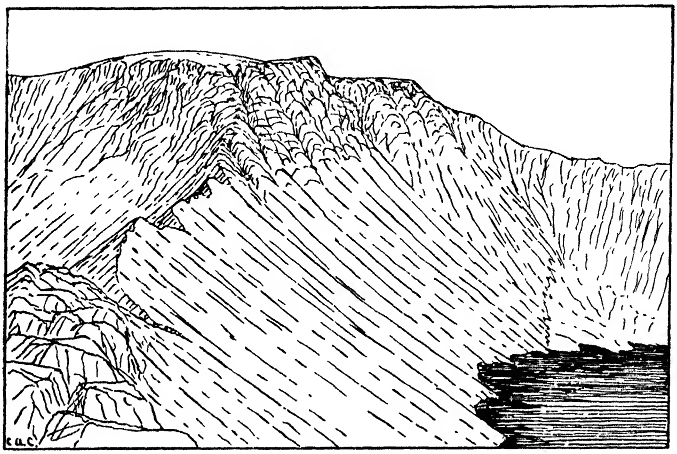

Fig. 54. Striding Edge arête and the summit of Helvellyn.

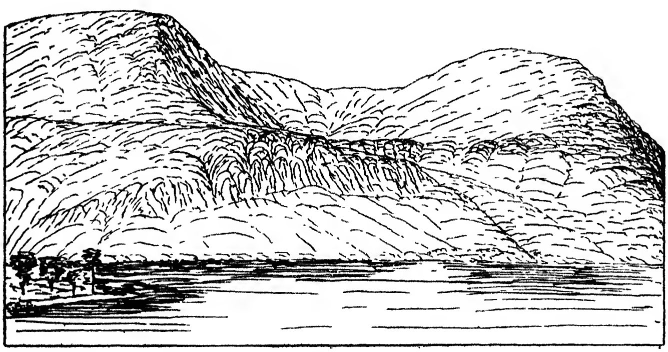

Fig. 55. Burtness Combe (cirque), Buttermere, Cumberland.

District of England (Pl. XXIV, 2; and Figs. 54, 55), where "modification has not gone on in a sufficient degree to destroy completely the rounded outlines of hills and ridges."[7]

[7] J. E. Marr, *The Geology of the Lake District*, p. 164, 1916.

Summits that have been overswept by an ice sheet, somewhat ice-shorn, and stripped at least of all residual weathered rock debris have very commonly been attacked by sapping on the flanks so that they have developed there both grouped and isolated cirques such as occur in East and West Greenland, Norway, and Scotland (Pl. XXIV, 1). Examples have been found also in the White Mountains (Presidential Range) of New Hampshire (Fig. 56).

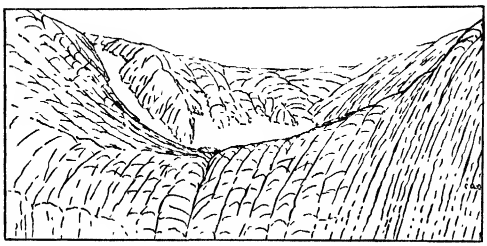

Fig. 56. Jefferson "Ravine," a corrie in the White Mountains, New Hampshire. (After a photograph by Douglas Johnson.)

Many corries so formed smoothly dimple mountain-sides so as to suggest the "armchair" simile first employed by Gastaldi.[8] The smooth armchair form of some Scottish corries in particular (Pl. XXVI, 1) may be an indication that they were in existence before the mountain summits had their asperities removed by the abrasive action of the ice sheet of the last glacial epoch. The major part of the excavation of cirques in ice-shorn regions has indeed been ascribed by Hobbs[9] to an episode in which isolated glaciers sapped actively prior to the

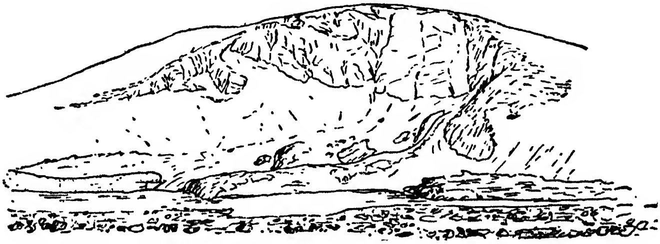

Fig. 57. The Galdhöpig cirque, in Norway. (After Richter.)

[8] B. Gastaldi, *Quart. Jour. Geol. Soc.*, 29, p. 396, 1873.
[9] W. H. Hobbs, Studies of the Cycle of Glaciation, *Jour. Geol.*, 29, pp. 370-86, 1921.

actual ice flood, when these were replaced by a continuous ice sheet. He thus explains the forms of the cirques of Norway, where ice-sheet abrasion has toned down the sharper features of an earlier phase of glaciation and "the last of the hollowed features of the

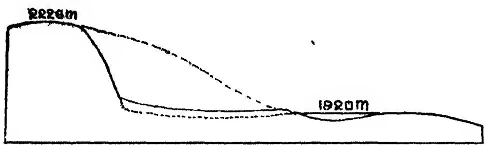

Fig. 58. The profile of the Galdhöpig cirque (Fig. 57). (After Richter.)

inherited surface to disappear are the increasingly truncated remnants of the cirques, which in their later stages take the form of an armchair-like depression." He cites the classic Galdhöpig cirque, figured by Richter (Figs. 57, 58), as an example.

After the shrinkage of a main ice sheet corrie glaciers would have again a possibly brief existence, or there might be recurrent glaciation on a minor scale. Thus re-sharpening of edges and, in particular, the development of rugged and shattered back walls might be accounted for by renewed sapping. There seems, however, to be no particular reason why more time should be allotted to glaciers for development of corries during the "advancing hemicycle of glaciation" (as Hobbs terms the glacial advance) than during the "receding hemicycle." It may be possible in some cases to distinguish in the same cirque features developed during advancing and receding glacierisation. This may be done only where owing to some combination of circumstances the cirque-cutting process has been feeble or has failed to function fully since the recession of the ice sheet. An example of this case is found on the Nugssuak Peninsula of West Greenland, where it appears that the continental glacier has temporarily advanced over cirques and, receding again very recently, has allowed them to re-emerge. "Their sides have been smoothed and polished by the overriding ice, and grooves and striae are cut high in the walls, where recent cirques should show only the effects of plucking and frost action."[10]

[10] M. Demorest, Glaciation of the Upper Nugssuak Peninsula, W. Greenland, *Zeits. f. Gletscherk.*, 25, p. 55, 1937; compare also C. S. Wright and R. E. Priestley, Glaciology, *British Antarctic Expedition 1910-1913,* p 150, 1922.

The theory that cirques in general date anteriorly to the main ice flood of the last glacial epoch fails to explain some "crater cirques"[11] in "tinds" (p. 194) and in particular the crater-like hollowed tind shown in Fig. 59. Had the cirque in this tind been

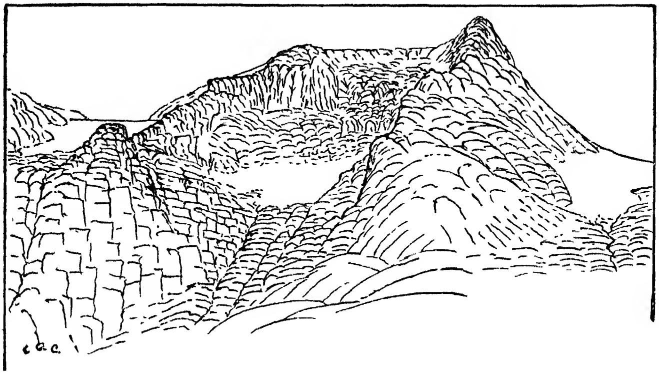

Fig. 59. "Crater cirque" in a "tind" (conical mountain) at Norangerdal, Norway.

in existence before the height of the ice flood, and before the outlet glacier channels on either side of the tind were excavated, it must itself have become the channel of an outlet glacier, and would then have been scoured out as deeply as the others with total destruction of the cirque. It has been argued that most of the cirques in the mountains of the eastern United States were developed subsequently to the recession of the continental ice;[12] and many of the corries of northern Labrador and north-east Greenland are regarded as of a similar late ("post-Wisconsin") origin.[13]

[11] T. C. and R. T. Chamberlin have noted that mountains hollowed out by "crater cirques," as they term them, are notable features of the coast of Norway (Certain Phases of Glacial Erosion, *Jour. Geol.*, 19, pp. 193-216, 1911). They are common also in Spitsbergen.

[12] Douglas Johnson, Date of Local Glaciation in the White, Adirondack, and Catskill Mountains, *Bull. Geol. Soc. Am.*, 28, pp. 543-552, 1917; Date of Local Glaciation in White Mountains, *Am. Jour. Sci.*, 25, pp. 399-405, 1933. Compare, however, the opinion of R. P. Goldthwait (Geology of the Presidential Range, *New Hampshire Acad. of Sci. Bull.*, 1, 1940) that cirque walls in the Presidential Range have been polished and striated by the continental ice sheet and that "no active mountain glacier existed afterwards or the grooved surface would have been plucked off."

[13] N. E. Odell, The Mountains of Northern Labrador, *Geog. Jour.*, 82, p. 209, 1933; The Glaciers and Morphology of the Franz Josef Fjord Region of North-east Greenland, *Geog. Jour.*, 90, pp. 111-125, 233-258, 1937.

Sapping

The relation of cirque-development to the presence of a névé in a mountain niche is no longer questioned. The niche being once formed or present as a feature of a preglacial landscape, the general mechanism of the enlargement of it can be readily grasped. Apart from the question of the origin or preparation of the initial or infantile niche, one can picture a cliff-sapping process making a more or less horizontal cut into the rocks of a mountain. Such a process develops a similar steep cliff wherever it operates—at the sea-margin, where erosion due to breaking storm waves cuts strictly horizontally into the land, or in the coves or amphitheatres of a winding valley in which a river vigorously undercuts and steepens cliffs in the process of lateral corrasion. The rocks above the cut, being unsupported, crumble down, and the more rapid the sapping the steeper and fresher the rock face (in rocks of the same kind).

It remains to account for the obviously rapid, and therefore very vigorous, cutting that takes place at the base of a cirque wall (or at the base of the steepest part of such a wall). Such undercutting is not in progress in the empty cirques of to-day: in these the upper walls are crumbling back to assume gentler slopes under the attack of physical weathering and are seamed by infantile or young ravines, while the basal parts of the walls are becoming every day more deeply buried beneath talus and alluvial cones (Pl. XX). There is reason to believe, however, that sapping is still vigorously in progress in those cirques still partly filled with névé, as are those, for example, of the alimentation zone of the Franz Josef and Fox glaciers, in New Zealand (Pls. XI, 1; XIV, 1), which indeed seem quite full.

This sapping at the base of the steep back wall of the cirque can be accounted for only by assuming that some kind of mechanical disintegration of the rock is going on there, and this must be frost-riving—the thaw-and-freeze process. Working alone in the open air such a process would soon slow down to zero pace as a protective layer of talus material buried the bedrock surface; but in association with a névé, which has the flowing motion of glacier ice, and which must in some way drag out and carry away frost-riven blocks of rock, continuity of the process of sapping by frost-riving can be understood.

It has been suggested that sapping by freeze and thaw is an open-air process going on actually above the névé, the function of which is merely to carry away, either on its surface or buried by fresh snows, the rock debris that falls upon it.[14] It has even been assumed that a hanging glacier that controls sapping may be of such small dimensions that the rock debris may glissade across its surface. When attention had been focussed on the possibility of an open crevasse (bergschrund) along the rear margin of a névé in some way controlling the depth to which physical weathering might extend, it was suggested as an extension of the hypothesis of sapping by weathering above the névé that debris might be swallowed through the bergschrund.[15] The whole hypothesis seems to have been formulated on the tacit assumption that cirques were sapped to their present dimensions (with walls in some cases 2,000 or 3,000 feet high) by glaciers or névés of insignificant thickness resting on the cirque floors below these great cliffs, as glacier remnants still do in some cases. It seems probable that some corries have been thus excavated, or at least enlarged, in very recent times, but this hypothesis fails to meet the case of the enlargement of already large cirques that have been filled with ice almost to the brim, as many cirques have been and some still are[16] (unless the enlargement of these cirques to full dimensions took place when glacierisation was much less intense than it became later).

As an alternative to the hypothesis of superglacial weathering some subglacial process must be invoked. The process of simple plucking has been suggested as a subglacial cause of sapping;[17] and it is recognised that plucking "is not confined to removal of pieces outlined by previously existing fissures."[18] It is generally maintained

[14] Theory attributed to A. Helland, Om Botner og Sækkedale, *Geol. För. Förh. Stockholm*, 2, 1875; adopted by E. Richter, Geomorphologische Untersuchungen in den Hochalpen, *Pet. Mitt. Ergänzungsheft* 132, p. 6, 1900; and favoured by E. de Martonne, *Traité de géographie physique*, 5th ed., p. 902, 1935.

[15] Apparently a misinterpretation by A. Penck (Glacial Features in the Surface of the Alps, *Jour. Geol.*, 13, pp. 15-17, 1905) and E. J. Garwood (Features of Alpine Scenery due to Glacial Protection, *Geog. Jour.*, 36, p. 313, 1910) of Willard Johnson's bergschrund hypothesis.

[16] Compare N. E. Odell, The Glaciers and Morphology of the Franz Josef Fjord Region of North-east Greenland, *Geog. Jour.*, 90, p. 246, 1937.

[17] D. J[ohnson], The Function of Melt-water in Cirque Formation, *Jour. Geomorph.*, 4, pp. 253-262, 1941.

[18] O. D. von Engeln, Palisade Glacier of the High Sierra of California, *Bull. Geol. Soc. Am.*, 44, p. 594, 1933.

however that there must be in progress some kind of subglacial disintegration, which, taking place at the base of the sapped rock wall, facilitates and speeds up its retreat.

Infraglacial disintegration of rock was suggested as a clue to the cirque-deepening process by Lorange (*fide* Helland).[19] The hypothesis was supported by Helland[20] and later by Penck,[21] who afterwards abandoned it, however; but geomorphologists grasped at the idea as it was embodied in the suggestive "bergschrund" hypothesis, as formulated by Willard Johnson and modestly advocated in his classic paper on glacial erosion[22] in explanation of his discoveries made during subglacial explorations many years earlier. According to this view the sapping thaw and freeze take place not actually under the ice of the névé but behind its steep rear margin. At the rear of the névé is the almost unfailing bergschrund (Pls. XII, 1; XXV, 1). This persistent crevasse is well known to Alpinists, who must cross it before passing from névé to rock for the final stage in the ascent of a peak, and it is generally considered to be a feature of every névé, though sometimes temporarily obscured by recent snows, filled thus in winter but reopened each summer. In order to test the hypothesis that the bottom of the bergschrund defined the level of sapping Johnson had himself lowered into such a crevasse to a depth of 150 feet, and his observations there strongly confirmed faith in the value of the hypothesis, though he would not claim that a complete solution of the sapping problem had been arrived at.

The Bergschrund

The bergschrund at the surface is a crevasse in the névé, but in the case investigated it passed at depth into a wide crevice between ice and rock. The rocky wall was wet, water dripped everywhere, and there was melting ice in fissures of the rock. There was thus evidence of a frequent alternation of freeze and thaw. A litter of

[19] A. Helland, *För. Förh. Stockholm*, 2, pp. 286-342, 1875.

[20] A. Helland, On Fjords, Lakes, and Cirques in Norway and Greenland, *Quart. Jour. Geol. Soc.*, 33, p. 164, 1877.

[21] A. Penck, *Morphologie der Erdoberfläche*, I, p. 399; II, p. 307, 1894.

[22] An Unrecognised Process in Glacial Erosion, *Science*, 9, p. 106, 1899; Maturity in Alpine Glacial Erosion, *Jour. Geol.*, 12, pp. 569-578, 1904. The hypothesis was first announced publicly in 1892 (*fide* Hobbs).

blocks of rock cumbered a rock floor, and the debris seemed in process of passing into the glacier to be carried away by it.

> There seemed to be definitely presented a line of glacier base, removed from five to ten feet from the foot of what was here a literally vertical cliff.
>
> The glacier side of the crevasse presented the more clearly defined wall. The rock face, though hard and undecayed, was much riven, its fracture planes outlining sharply angular masses in all stages of displacement and dislodgement. Several blocks were tipped forward and rested against the opposite wall of ice; others, quite removed across the gap, were incorporated in the glacier mass at its base. Icicles of great size, and stalagmitic masses, were abundant; the fallen blocks in large part were ice-sheeted; and open seams in the cliff held films of this clear ice. Melting was everywhere in progress, and the films or thin plates in the seams were easily removable. These thinning plates, especially, were demonstrative of alternate freezings and thawings in short time intervals, probably diurnal. Without, upon the cirque or amphitheatre wall, above the glacier, such intervals would be seasonal . . .
>
> The glacier is a cover, protective of the rock surface beneath it against changes of temperature. Probably the bed temperature does not fall below that of melting ice. Hence, if (in summer) the bed at the wall foot is exposed through the open bergschrund to daily temperature changes across the freezing point, frost weathering must be sharply localised.[23]

Apart from reports that some sapping glaciers in the Andes, Antarctica, and north-eastern Greenland are apparently without bergschrunds the most troublesome part of the bergschrund hypothesis is the difficulty of postulating sufficiently deep bergschrunds, for there are cirques bounded by nearly vertical cliffs more than 2000 feet high.[24] In some cirques, notably in those of California examined by Johnson and also by Gilbert[25] the steep back wall is of quite a moderate height, however, and below a sharp angle, which defines the "schrund line", as it was called by Gilbert (Pl. XX, 1; Fig. 69), the descent continues at a much gentler declivity.

[23] Willard D. Johnson, *loc. cit.* (22) (1904).

[24] For example, in the island of Skye. W. V. Lewis, *Geol. Mag.*, 75, p. 258, 1938.

[25] G. K. Gilbert, Systematic Asymmetry of Crest Lines in the High Sierra of California, *Jour. Geol.*, 12, pp. 579-588, 1904.

Below this line also the lower slope and the floor of the cirque are obviously smoothed and presumably also worn by abrasion. It has been suggested that a schrund line, which indicates the sapping level, marks also the level at which ground water has seeped out of the rock wall behind the névé and that the level of this ground water (which has become available for freezing in rock crevices) has controlled the sapping process.[26] It might perhaps determine whether the saw cut made by sapping should be horizontal or inclined.

In many large cirques a schrund line, or re-entering angle in the back wall, the presence of which would indicate a sapping level

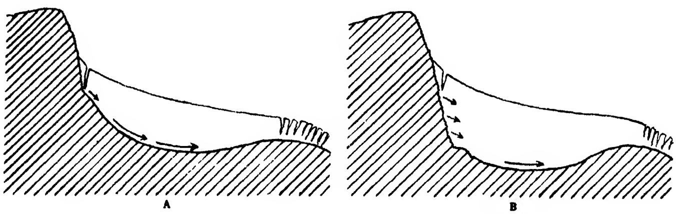

Fig. 60. Cirque profiles. A, with "schrund line"; B, with high, near-vertical back wall. (After Lewis.)

above the floor, is not found. In numerous British cirques examined by Lewis,[27] for example, the very high and nearly vertical back and side walls reach to the floors, which they meet almost at a right angle, and lakes on the floors commonly lap the back walls (Fig. 60).

Melt-water Freeze and Thaw

In cases where the depth of the sapping level has exceeded the probable depth of a bergschrund, or where there has been for some reason no bergschrund, it has been suggested that alternate freeze and thaw may have gone on in the crevices of the rock wall behind a névé or corrie glacier. Above the névé corrie walls are observed to be wet in summer owing to the melting of snow, and water trickles down behind the névé, developing in some cases an open

[26] T. C. and R. T. Chamberlin, Certain Phases of Glacial Erosion, *Jour. Geol.*, 19, pp. 193-216, 1911.

[27] W. V. Lewis, *loc. cit.* (24).

cleft along the rock wall. Water may issue also from springs behind the névé.[28]

The hypothesis has long been applied to subglacial erosion in general and is clearly stated by J. Geikie as follows:

> The constant outflow of water shows that infraglacial melting goes on all the year round. The temperature at the bottom of the ice oscillates about the freezing point, and as a glacier flows on its way thawing and freezing must be continually taking place. In this way joints are no doubt opened, rock masses loosened, and smaller fragments become more readily plucked and dragged out of place.[29]

The process thus invoked is quite apart from possible control of temperature through a crevasse open to the atmosphere, but depends on the internal physical condition of the glacier. Whatever the temperature of the atmosphere, the heat of the earth must keep the basal ice of all except some very thin glaciers at the melting point (pp. 130-1).

Chamberlin and Chamberlin[30] point out that the water present will become ice wherever tension is developed during glacial movement, as in the lee of rock projections, and that such freezing will lead to plucking away of projecting rocks. Nansen has noted also another possible cause of small changes of pressure which may result in freeze and thaw: "The pressure under water filling holes in the ice will be greater than under the ice at the same level, owing to the considerably higher density of the liquid water. If the temperature is at melting point the ice may thus melt under the water, and this may continue down to the bottom of the glacier, provided that the holes remain full of water. But as soon as the pressure is reduced, the water will again freeze under the glacier. Such holes, more or less filled with melting water, may often be formed along the edges of the glaciers, between the ice and the

[28] T. C. and R. T. Chamberlin, *loc. cit.* (26); I. Bowman, *The Andes of Southern Peru,* pp. 296-305, 1916; O. D. von Engeln, Palisade Glacier of the High Sierra of California, *Bull. Geol. Soc. Am.,* 44, p. 593, 1933; N. E. Odell, *loc. cit.* (16); W. V. Lewis, A Melt-water Hypothesis of Cirque Formation, *Geol. Mag.,* 75, pp. 249-265, 1938; W. V. Lewis, The Function of Melt-water in Cirque Formation, *Geog. Rev.,* 30, pp. 64-83, 1940.

[29] J. Geikie, *Earth Sculpture,* p. 180, 1898.

[30] *Loc. cit.* (26).

rock, and in this manner the disintegration of the rock may be increased."[31]

Relation of Sapping to Aspect

The effects of sapping beneath the ice margin were found by Gilbert[32] to be most strongly marked (as shown by the development of a nearly vertical wall on one side only) in those parts of cirques and upper troughs of former Californian glaciers where the walls faced north and east, situations in which snow-accumulation had been greatest. He related this to a movement of névé ice away from the walls against which snow accumulated most rapidly. Such movement might facilitate sapping by keeping open a bergschrund (and possibly in other ways also). The contrast of steeply and gently glaciated cirque slopes, where those of adjacent cirques intersect, is shown in one of Gilbert's photographs reproduced as Plate XXVI, 2. Helland in Norway, Partsch in Germany, Lewis in Britain, and a great many other observers have noted that (in the Northern Hemisphere) there are far more corries on northward- and eastward-facing slopes than on those with a southerly or westerly aspect.

Migration of the Snow-line

Whether or not it be closely associated with definite bergschrunds there can be no doubt that cirque-wall sapping is related to "nivation" (Chapter XV) and in general to freeze-and-thaw phenomena in the vicinity of the snow-line. A relation of cirques to the snow-line has been quoted by Partsch and others.[33] The optimum conditions for cirque development occur, it seems, in a zone in which the average annual temperature is somewhere near freezing point.[34] Where the temperature is too low—as, for example, it is even at sea-level on parts of the Antarctic coast at the present day—the process is almost at a standstill. In these

[31] F. Nansen, Strandflat and Isostasy, *Vidensk. Skrifter, M-N. Kl.*, 1921, No. 11, p. 26, 1922.

[32] G. K. Gilbert, *loc. cit.* (25).

[33] J. Partsch, *Die Gletscher der Vorzeit in den Karpathen und den Mittelgebirgen Deutschlands*, Breslau, 1882; J. Geikie, *Earth Sculpture*, p. 233, 1898.

[34] 34° F., according to Griffith Taylor, Some Geographical Notes on a Model of the National Park at Mt. Field, Tasmania, *Jour. and Proc. Roy. Soc. Tas. for 1921*, pp. 188-198, 1922.

places there are many enormous cirques, however, such as the Walcott Cirque on Mt. Lister, which Taylor has described as "one of the finest in the world, since it is about ten miles wide and has a rear wall about 10,000 feet high," and active cirque excavation must, it seems, have gone on in a milder epoch anterior to the present frigid stagnation.[35] Taylor has traced the migration of the snow-line in the south-western Pacific region (Fig. 61).

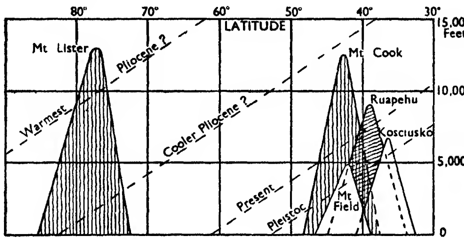

Fig. 61. Migration of cirque-wall sapping level in the South-western Pacific region. (After Taylor.)

Both in Antarctica and in the Lofoten Islands (which suffered only local glaciation in the last glacial epoch) it has been recorded that large cirques are present with floors below the present sea-level; and very similar forms appear in photographs of northern Labrador.[36]

Of considerable interest in relation to the hypothesis that the development of cirques is confined to the vicinity of the snow-line is a suggestion made by Douglas Johnson[37] that high-walled cirques owe this characteristic to progressive deepening by shallow glaciers —in other words, that the saw cut resulting from a sapping process localised at the bottom of the bergschrund of a thin corrie glacier slants back downward in such cases so that by undercutting it develops a superglacial back wall of progressively increasing height, in front of which a rock floor is lowered by abrasion. This hypothesis may imply in the case of some cirques now very

[35] Griffith Taylor, Glaciation in the South-west Pacific, *Proc. 3rd Pan-Pacific Congress* (*Tokyo*), pp. 1819-1825, 1926.

[36] N. E. Odell, The Mountains of Northern Labrador, *Geog. Jour.*, 82, pp. 193-210, 315-325 (superbly illustrated—see especially photograph opposite p. 316), 1933.

[37] D. J[ohnson], *loc. cit.* (17), Fig. 3, p. 260.

deeply filled with firn, as seems to be true of those accommodating the névés at the heads of the Franz Josef and Fox glaciers (New Zealand), that these cirques are relict forms in the sense that they must have been excavated to their present form under atmospheric conditions, perhaps of an interglacial epoch, warmer than those now prevailing.

"Two-storied" cirques occur fairly commonly. There are examples in New Zealand (Fig. 62 and Pl. XXIII, 2), and good Norwegian examples are figured by Flückiger,[38] while "cirque stairways" have been studied especially in the Carpathian Mountains.[39] Richter has noted, however, that it is impossible to draw the line satisfactorily between these latter and stepped valley profiles.[40] Cirques at higher and lower levels may mark successive positions of the snow-line; but it is not impossible to imagine conditions favouring contemporary development of some cirques that form successive steps, if reconstructed glaciers have been formed in lower niches out of avalanche ice descending from higher cirques.

It has often been remarked that the upper walls of large cirques are rather characteristically fretted by smaller corries[41] like those revealed by air photographs of the summit of Mitre Peak (Pl. XXV, 2), which appear to be of more recent origin than the main cirques. Even where the walls of a lower-level cirque are very steep, ledges may have developed which have been controlled by structural flaws in the rocks, and on such ledges small névés may accumulate and dig themselves in to make corries of an upper storey. It is possible also that a second generation of corries may be opened up when glacial conditions recur and small snowfields are formed in ravines that have been cut by streams in the wall of a more ancient cirque in a mild climatic interval. There is in some cases a more or less regular row of these on the upper walls of a main cirque.

[38] O. Flückiger, Glaziale Felsformen, *Pet. Mitt. Erganzungsheft,* 218, Abb. 43, 1934.

[39] E. de Martonne, *Bull. Soc. Sc. Bucharest,* 9, 1900.

[40] E. Richter, Geomorphologische Untersuchungen in den Hochalpen, *Pet. Mitt. Ergänzungsheft* 132, pp. 54, 103, 1900.

[41] O. D. von Engeln, *loc. cit.* (28). See also W. M. Davis, *Die erklärende Beschreibung der Landformen,* Fig. 175, 1912.

Cirque Floors

Cirque floors have been smoothed by glacial corrasion, and the same process has excavated and hollowed them out to some extent. Below the foot of the sapped upper part of the back wall, which is steep and ragged, and separated from it in some cases at least by a definite change of slope at a schrund line (Pls. XX, 1; XXVII, 2) is a rock surface that is by comparison extraordinarily smooth and may be even polished in parts, though not planed, and thus affords evidence of abrasion.

Some observers[42] have come to the conclusion, indeed, that the whole, or almost the whole, excavation of the amphitheatre is due to this process, and allow for only a little sapping to steepen the back wall, the full height of which cannot generally be accounted for by corrasion. It is commonly assumed as a part of this theory, however, that rock fragments are loosened by freeze and thaw beneath a cirque glacier to facilitate the process of their removal (p. 181). Some light on the process of cirque-deepening by abrasion may be afforded by a theory of névé movement advanced by Streiff-Becker,[43] which has been summarised as follows:

> The ends of ice layers adjacent to the bergschrund become well filled with rock fragments. Because the maximum velocity is near the base, these rocks do not move forward horizontally into the firn mass. Instead, as the layers of ice are rotated into an inclined position, the rock-filled ends remain near the rock floor, eroding it as they sweep over it.[44]

Cirque Lakes

The whole floor as thus smoothed and roughly levelled is commonly actually concave, so as to hold a lake or tarn at the present day (Frontispiece and Fig. 62), and the lip of the cirque is thus walled across by a bar of bedrock, which is smoothly rounded off by abrasion (Fig. 62 and Pls. XX, 1; XXIV, 2).

[42] See, for example, A. Penck, *loc. cit.* (21), 2, p. 307; E. de Martonne, *loc. cit.* (14); F. Nussbaum, Beobachtungen über Gletschererosion, *C-R. XV Internat. Géogr. Congr.*, 2, 1938.

[43] R. Streiff-Becker, Zur Dynamik des Firneises, *Zeits. f. Gletscherk.*, 26, pp. 1-21, 1938.

[44] Abstract by A. van Burkalow in the *Journal of Geomorphology*, 2, pp. 389-390, 1939.

Morainic heaps of the rock debris that has been carried forward from the retreating back wall by the glacier or plucked out in the process of excavation of the floor are present in small or large amount, in some cases sufficient to build an arcuate ridge (moraine loop) forming a dam which raises the level of the cirque-floor lake. The drainage collected in the cirque, whether there is a lake on its floor or not, forms an outflowing stream over the bedrock lip, and so short a time may this stream have been in existence (a mere few thousand and in some cases only a few hundred years)

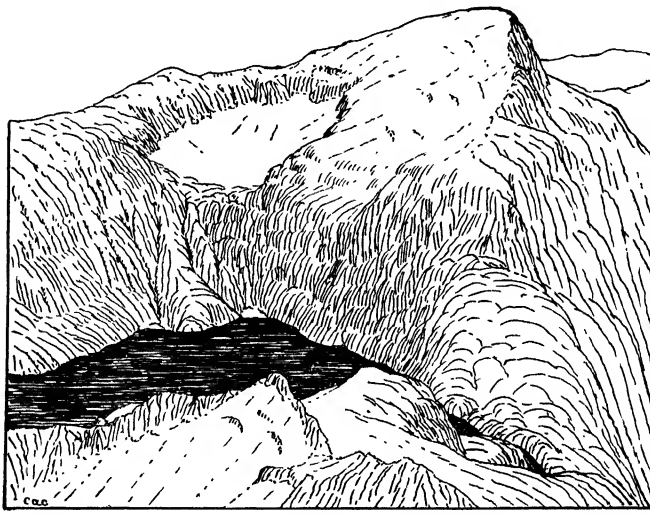

Fig. 62. Two-storied cirque (cirque stairway) and cirque lake, Lake Quill, above the Sutherland Falls, Fiordland, New Zealand. (From an air photograph by V. C. Browne.)

that it has made as yet no notch of appreciable magnitude in a hard-rock lip. In some cases it has cut a narrow V trench of insignificant proportions, and almost invariably the stream cascades down the rock slope in front of the cirque.

Observations made on cirques with hollowed floors have fostered the theory that they all have been made by corrie glaciers—that is to say, by hanging glaciers with the terminal face at the lip of the cirque, where the presence of a moraine may show at least that the terminal face has halted in this position for a

long or short period during the final dwindling. On the theory that erosion is greatest where the ice is thickest[45] the deep corrasion of a corrie floor can be explained as having occurred when the glacier has ended at the lip, or when, at any rate, no more than a thin ice-fall has extended down the slope beyond it. This explanation was adopted by Helland, who characterised "tarns" as "the last works of the glaciers in the cirques."[46] Though many similar suggestions have been made,[47] and the theory satisfactorily explains many corries, it is of more doubtful value as an explanation of valley-head cirques. From analogy with the longitudinal profiles of the floors of troughs that have contained glacier tongues (Chapter XIX), in which it appears that many rock-rimmed hollows have been excavated beneath trunk glaciers, it may be suspected that some cirque floors have been hollowed out under the heads of long ice-streams.

It was remarked by Helland that "the cirques which occur isolated in the mountains are not essentially different from the valleys which end in a cirque,"[48] and much more recently Lewis[49] has echoed this opinion after a searching examination of British cirques. The cause of the excavation of concave floors near valley heads is not thoroughly understood, but the feature is certainly not confined to hanging cirques. It was the hollowed floor in the valley-head (Pl. XX, 2) that led Willard Johnson to characterise glaciated valleys as "down at the heel."[50] A simple suggestion that has been made in explanation of it connects it not with sub-glacial corrasion but with headwall sapping, which need not work quite horizontally, but may, as has been noted by Hobbs[51] and by Chamberlin, excavate in some inclined direction, which

[45] M. Close, On Some Corries and their Rock Basins in Kerry, *Jour. Roy. Geol. Soc. Ireland,* 2, p. 236, 1870.

[46] A. Helland, On Fjords, Lakes, and Cirques in Norway and Greenland, *Quart. Jour. Geol. Soc.,* 33, pp. 142-176, 1877.

[47] See, for example, W. M. Davis, Glacial Erosion in France, Switzerland, and Norway (1900), reprinted in *Geographical Essays,* pp. 671-672; A. Penck, *loc. cit.* (15), p. 16.

[48] A. Helland, *loc. cit.* (20), p. 165.

[49] W. V. Lewis, *Geol. Mag.,* 75, pp. 257-258, 1938.

[50] As quoted on p. 158.

[51] W. H. Hobbs, *Characteristics of Existing Glaciers,* p. 62, 1911.

may be downward as well as backward, at some stage during the excavation of a cirque.[52] This may occur possibly at an early stage. With this may be compared the suggestion (p. 183) that thin corrie glaciers may excavate high-walled cirques by a similar process. The hypothesis cannot be applied very satisfactorily, however, in explanation of the floor forms of cirques with high schrund lines.

Not only the large-scale excavation required to make some valley-head cirques, but the fact also that many of these are merely the topmost steps of stairways of similar forms,[53] make it highly improbable that all such hollowing can be referred to the brief period when relic glaciers had their melting fronts at the cirque lips. The problem is bound up with the general question of glacial corrasion, however, as it affects the profiles and major features of the floors of glaciated valleys (Chapter XIX).

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[52] T. C. and R. T. Chamberlin, Certain Phases of Glacial Erosion, *Jour. Geol.*, 19, p. 212, 1911.

[53] For example, the Lota corrie, in Skye, described by Lewis, *loc. cit.* (28).

CHAPTER XV

Intersecting Cirques; The Destruction of Mountains; Nivation

SETTING ASIDE for the present all discussion of the mechanism of glacial erosion, one may turn back to an explanation and description of upland features developed in the process of cirque enlargement by sapping.[1]

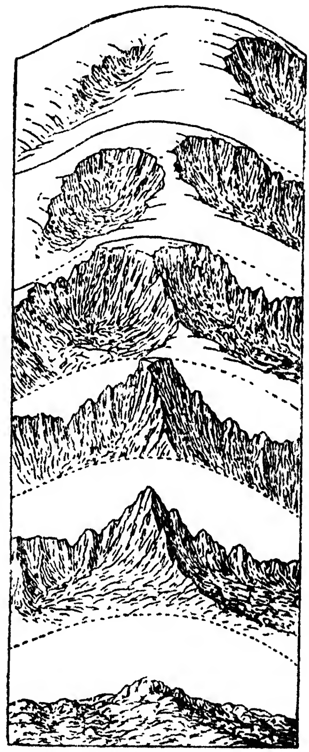

Fig. 63. Stages in the destruction of a subdued mountain by cirque-wall sapping. (After Davis.)

When a scalloped or "channeled"[2] upland in the "stage of youth" of the cycle of mountain glaciation (as exemplified by the upland features of the Uinta Mountains — Fig. 49) passes beyond the early "biscuit-cutting" stage[3] and reaches adolescence it begins to show the effects of intersection, or "inosculation" of cirques, where adjacent back and also perhaps side walls of these approach and eventually intersect one another (Fig. 63; Pl. XXVII, 1). Examples are seen on Snowdon (Fig. 53). Isolated remnants of preglacial landforms may still survive (Figs. 63, 78; and Pl. XXVII, 2), and these afford evidence of the progressive replacement of a former landscape by features developed by glacial sapping. The most convincing examples

[1] It may be hoped that the reader will be willing to accept the doctrine of sapping as sufficiently "orthodox" to be made the basis of an explanation of Alpine summit forms, in spite of the recent pronouncement that there is "a more orthodox view" that "corries are relatively static elements not susceptible of considerable enlargement." (Wooldridge and Morgan, *The Physical Basis of Geography,* p. 378, London: 1937).

[2] So termed by W. H. Hobbs, *Jour. Geol.,* 29, p. 375, 1921.

[3] So named from the "dough on the biscuit board" simile of Willard Johnson (Chapter XIII).

are found in regions where subdued, rounded mountain summits were formerly common. In the replacement of these convex by concave cirque profiles is seen the transition to glacial maturity of dissection.

The landscape now becomes "Alpine", exemplified in parts of the High Sierra of California and in most of the high mountain ranges of middle latitudes, such as the Swiss Alps and the Southern Alps of New Zealand, which are situated in regions of ample precipitation and have supported well-nourished glaciers. This is the stage of glacial dissection referred to in Chapter XIII as a "fretted upland".

Aretes and Horns

Among the detail features that result from cirque-wall intersection the most characteristic is the "arête", if one may limit the use of this term to the designation of sharp-edged dividing walls between inosculating cirques. Cirque-walls are not generally smooth, and, especially where they are very steep, their intersection may

Fig. 64. Detailed diagram of the sharpening of a lofty peak by inosculation of cirques, producing a horn. (After Davis.)

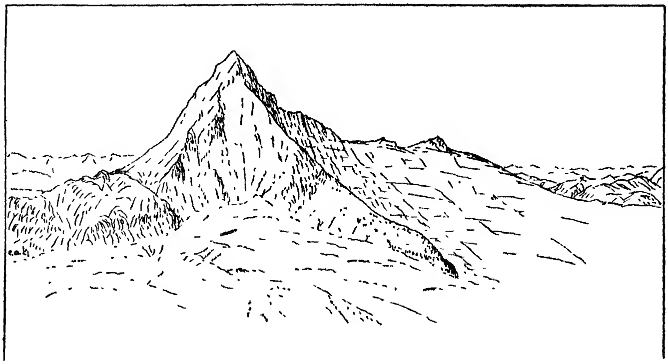

Fig. 65. Mt. Aspiring, the "Matterhorn" of New Zealand, a glacially sharpened horn, which is still surrounded by glaciers. (Drawn from a photograph.)

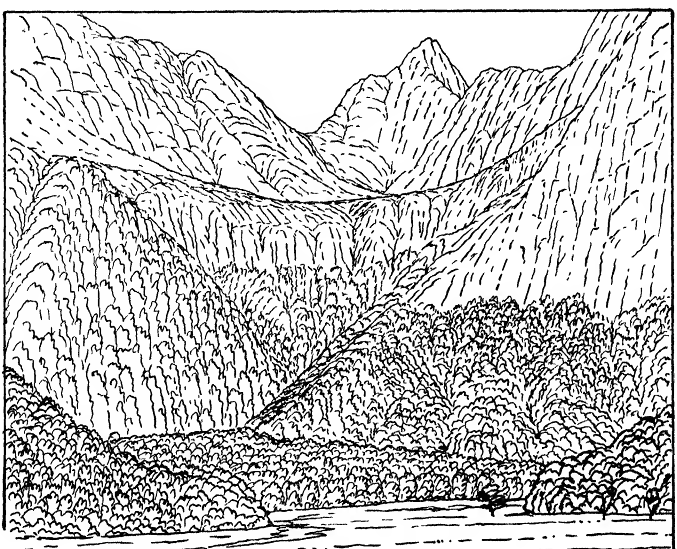

Fig. 66. Col formed by inosculating cirques on the divide between the Routeburn and Hollyford valleys, New Zealand.

produce strongly serrate arêtes ("comb ridges" of Hobbs), surmounted by sharp rock pinnacles ("gendarmes") between steep gullies ("chimneys") of the cirque-walls. Two cirques intersect to produce an arête, but three or more may be simultaneously attacking a peak in front, flank, and rear, so that arêtes radiate from an unconsumed summit (Figs. 63, 64, 65); and as the sapping process continues and the residual area dwindles and disappears a sharp-pointed summit or "horn" is developed, bounded on all sides by sapped slopes, which meet in the arêtes (Pl. XXVIII, 1 and 2). The classic example of a horn on a large scale is the imposing peak of the Matterhorn, in Switzerland (Pl. XXVIII, 1). Mt. Aspiring (Fig. 65) is the "Matterhorn" of New Zealand.

Cols and Passes

Where arcuate cirque walls with steep to moderate slopes intersect, and sapping continues, rapid lowering of intermediate back-wall arêtes reduces them to gaps or cols (Figs. 53, 66); and, in the common case where the floors of inosculating cirques are at different levels, the névé of a higher cirque spills through a col to join another névé at a somewhat lower level. This is an example of glacial "transfluence", a variety of "diffluence".[4] When transfluence takes place thus at a high level it results in a kind of glacial "piracy", which may have permanent results in diverting post-glacial drainage, and a gap so formed and deepened also by abrasion during the ice flood may be followed after the ice melts away by a river which has been given the right of way through a preglacial divide. Whether such a low-level gap is scoured out or not the deepening by abrasion of a col opened first by sapping may be at least sufficient to convert it into an easily accessible U-shaped pass in the postglacial landscape (Pl. XXX. 1), and many of the geographically important passes in the European Alps and other mountain ranges have originated in this way.[5]

Possibly the same explanation may be correctly applied to low-level corridors extending right through some mountain ranges that have been heavily glaciated (for example, the deeply cut lake

[4] A. Penck, Glacial Features of the Alps, *Jour. Geol.*, 13, p. 10, 1905.
[5] A. Penck, *loc. cit.* (4), p. 11; J. Sölch, Studien über Gebirgspasse. . . , *Forsch. D. Landes- und Volksk.*, 17, pp. 195, 206, 1905.

basins transecting the Andes of Patagonia). Some well-known examples of such deep cuts, however, are relics of the effects of concentrated ice-sheet flow over ranges through preglacial notches, which have been deepened in the process, as in the case of the lake basins on the axial divide of Scandinavia; and others are examples of glacial diffluence at places where distributing valley glaciers have spilled through and deepened valley-side notches.

Tinds

An additional form of glacially isolated mountain peak has been ascribed to lateral cirque-enlargement (Fig. 67), assisted in

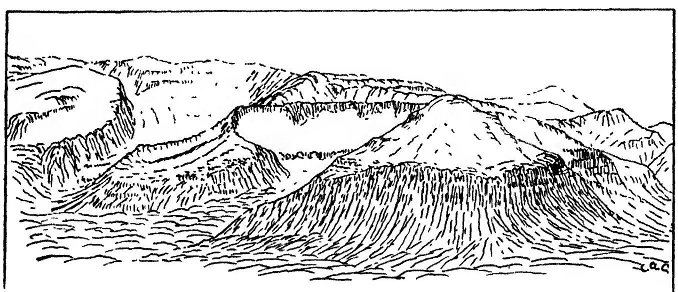

Fig. 67. Lateral enlargement of cirques in Spitsbergen. (Drawn from a photograph.)

some cases, however, by the abrasive process that ploughs out troughs. Glacial "monuments", as defined by Hobbs,[6] are pyramidal peaks isolated at the ends of upland spurs between cirques of large dimensions. In the stage of glacial "maturity" of dissection the *lateral* walls of these already intersecting cirques are lowered by continued sapping at the rear of the surviving spur-end "monuments"[7] in such a manner as to isolate them. Numerous examples of such forms, due to lateral expansion of cirques and the headward parts of troughs, are seen in the northern Rocky Mountains, in Montana and Canada, and examples from Spitsbergen, the European Alps, and New Zealand are illustrated in Figs. 68 and 69 and Pl. XXXIV, 2. The distinction between "monuments" and the

[6] W. H. Hobbs, *loc. cit.* (2).

[7] For "monument" used with another meaning see Fig. 1; also p. 8.

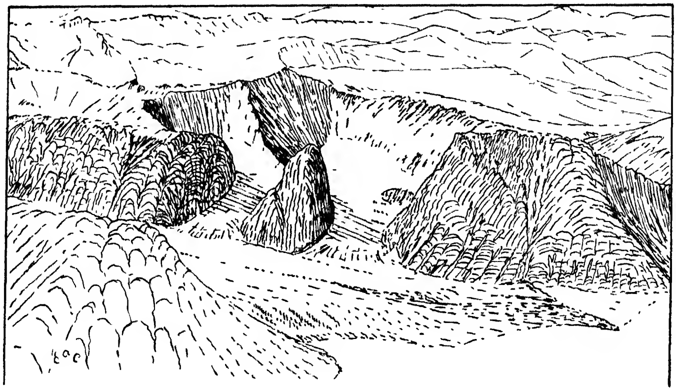

Fig. 68. A "monument," "gate post" (Flückiger), or tind between two laterally enlarged cirques in Spitsbergen. (Drawn from a photograph.)

earlier defined "tinds",[8] which are pyramidal peaks isolated by glacial erosion at the margin of the Norwegian plateau (Fig. 75), seems insufficient to warrant the introduction of another term, and all these features are best termed tinds.

Peaks isolated in this way have been recognised on the eastern face of the Sierra Nevada of California—a great fault scarp the crest line of which in the vicinity of Mt. Whitney has been

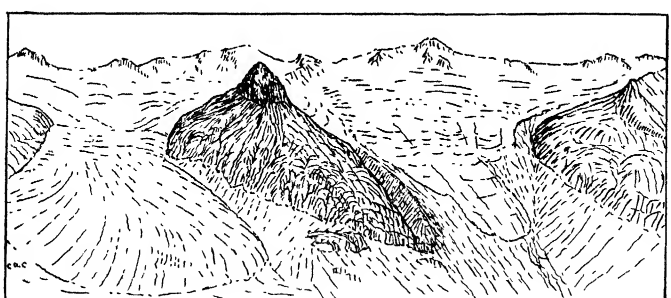

Fig. 69. A tind isolated by cirque-widening, and showing a schrund line, Zemmgrund glaciers, eastern Alps. (Drawn from a photograph.)

[8] W. H. Hobbs, *Characteristics of Existing Glaciers*, p. 79, 1911. "Tind" in Norwegian means simply a peak, but there can be no objection to its use in English as a more strictly defined geomorphic term, on the analogy of "cuesta" and "ria" (compare W. M. Davis, The Principles of Geographic Description, *Ann. Ass. Am. Geog.*, 5, p. 82, 1915.

cut back by cirque erosion. In this process it has been observed that peaks have been left standing out as "stacks are left upon a wave-cut terrace by the recession of the sea-cliff."[9]

Glacial Peneplanation

Destruction of mountainous relief by glacial "peneplanation" is a theoretical abstraction in that no cases of such levelling down of mountains are known with certainty; but, if a glacial peneplain exists anywhere, it may be expected to exhibit a mammillated cirque-floor-like relief, which is largely a product of sapping followed by abrasion, such as Davis imagined in the final deduced stage in his diagram reproduced herewith as Fig. 63. Though he was probably mistaken, Richter[10] attributed the Norwegian plateau to such an origin.

Various observers of glaciated summit forms have speculated as to the possibility of extensive glacial truncation of mountains. Thus Lawson[11] has remarked:

> In viewing from Mt. Whitney [in the Sierra Nevada] the revolution in the geomorphy . . . which has been wrought by ice sculpture, and particularly by the gnawing of the cirques into the heart of the mass, one cannot but reflect that, had glacial conditions continued for twice as long as they actually did, or at most three times as long, the entire summit tract would have been obliterated, in the sense of being truncated to the level of the cirque floors. It is interesting to reflect further that this process of truncation, as it approaches completion, would not only remove the mountain tops, but thereby also do away with glaciation. Glaciation in the high mountains, in so far as it depends upon altitude, is, therefore, a process which automatically terminates.

The Arctic Strandflat

The process of glacial headwall sapping, or a nivation process closely allied to it, deserves consideration as an explanation of the origin of the remarkable feature termed by Reusch and by Nansen

[9] A. C. Lawson, The Geomorphogeny of the Upper Kern Basin, *Univ. Calif. Publ. Bull. Dep. Geol.*, 3, p. 360, 1904.

[10] E. Richter, Geomorphologische Beobachtungen aus Norwegen, *Sitz. Ber. k.k. Akad. Wien*, M-N. Cl. 105 (1), 1906.

[11] A. C. Lawson, *loc. cit.*, p. 360; compare E. de Martonne, *Traité de géographie physique*, 2 (5th ed.), p. 928, 1935.

the "strandflat", which borders Norwegian and Arctic coasts.[12] It is a partly submerged, rocky, coastal lowland, very extensive in some regions and in Norway continuous for hundreds of miles, though trenched by fiords and straits. It varies considerably in elevation from place to place as a result of vertical (isostatic)

Fig. 70. The strandflat fringing the south side of Lofoten Island, Norway. The cliff at the right is 1,755 feet high. (After a sketch by F. Nansen.)

Fig. 71. Strandflat, north-west coast of Norway.

movements which Norwegian and Arctic coasts have undergone. The surface of the strandflat is notably roughened by glacial abrasion, so that an outer fringe of the lowland consists of half-submerged skerries (Pl. XXIX, 1). It is backed by very high and steep cliffs which descend to a sharp re-entering angle at the base (Pl. XXIX, 2; and Figs. 70-72).

It is generally agreed that the strandflat cannot have been reduced to its low level entirely by glacial abrasion such as has been the cause of the deep excavation of fiords in the highland at the rear and the extensions of these across the coastal lowland itself. It has, however, been covered by a piedmont fringe of ice which has abraded it to the extent of roughening the minor relief, though, in some parts, without destroying its essentially level character. The ice on it was thin and sluggish as compared with that in adjacent fiord troughs.

The strandflat must be regarded, therefore, either as a relic of the preglacial landscape or the product of some process of

[12] F. Nansen, Strandflat and Isostasy, *Vidensk, Skrifter, M.-N. Kl. 1921,* 11, 1922.

lateral corrasion or sapping which operated during the Glacial Period. The former is the hypothesis favoured by Ahlmann,[13] who is convinced that the lowland existed in preglacial times as a peneplain strip in the coastal area; and a precisely similar explanation of a strandflat in Alaska, which is remarkably like that of Norway, has been given by Gilbert.[14] He has termed it a "low peneplain" and has remarked: "Probably none of the original surface remains, but the glacial degradation must have been locally quite moderate, or the general plain character would not have survived."

Fig. 72. The strandflat, Helgeland Coast, Norway. (After a photograph by Ahlmann.)

Nansen, on the other hand, favours a hypothesis of retrogressive sapping along shorelines, especially in the lower reaches of fiords after these have been deepened by glacial abrasion, which may have taken place in an early glacial epoch, leaving time for interglacial strandflat development. Marine abrasion by waves, though not excluded by Nansen as a contributing process, must be of minor importance in sheltered channels, and the chief cause of sapping seems to have been a nivation or freeze-and-thaw process at the rear of cliff-foot snow accumulations, which developed into an "ice-foot", or "fringing glacier",[15] along the shore. Both Holtedahl[16] and Fleming[17] have observed a narrow strandflat in Graham Land, West Antarctica, with relics of formerly more

[13] H. W. Ahlmann, Geomorphological Studies in Norway, *Geografiska Annaler,* 1, 1919; *Scientific Results of the Swedish-Norwegian Arctic Expedition . . . 1931,* pp. 108-110, Stockholm, 1934; Repräsentative Beispiele . . . Glazialerosion in Schweden and Norwegen, *CR., Congr. Internat. Géogr. Amsterdam,* 2, p. 9, 1938.

[14] G. K. Gilbert, Glaciers and Glaciation, *Harriman Alaska Expedition,* 3, p. 131, 1904.

[15] So called by W. L. S. Fleming, Relic Glacial Forms on the West Coast of Graham Land, *Geog. Jour.,* 96, pp. 93-100, 1940. ("Strandflat glacier" of Holtedahl.)

[16] O. Holtedahl, On the Geology and Physiography of Some Antarctic and Sub-Antarctic Islands, etc., *Sci. Res. Norweg. Antarctic Exp.,* 3, pp. 146-168, 1929.

[17] *Loc. cit.* (15).

continuous fringing glaciers lying on it at the bases of cliffs which have obviously been sapped back and steepened by a process similar to that responsible for the steepening of cirque walls. Planation of islands off this coast is almost certainly the result of a similar process, and the application of such a hypothesis in explanation of strandflats in general seems sufficient to account for their form and distribution along high-latitude fiord-indented coasts.

The ice-shorn coastal bench at Angmagssalik,[18] on the east coast of Greenland, if not of quite similar origin seems at least closely analogous. The bench might almost be described as an ice-cut

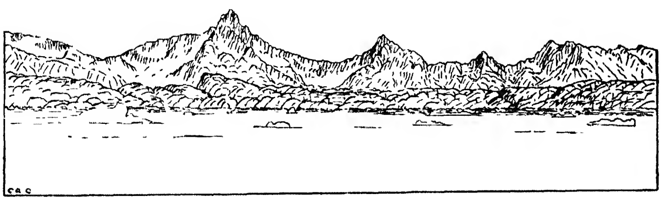

Fig. 73. A rocky foreland ("strandflat") at Angmagssalik, south-east Greenland, which may be an ice-cut pediment left by mountain-front retreat where trough-floors coalesce as the spurs between them are destroyed by lateral glacial corrasion. (Drawn from a photograph by C. and A. Lindbergh.)

"pediment", for it has the appearance of being developed by coalescing trough-floors as the spurs between adjacent troughs occupied by glaciers have been sapped away by some process of lateral glacial corrasion (Fig. 73).

Antarctic Cirques and Troughs

Cirque development by nivation and sapping either is now or has been in the past in vigorous progress on scarps of the stepped ascent from McMurdo Sound to the crest-line of Mt. Lister (the margin of the Antarctic plateau).[19] Corries are found in infantile and young stages of their development on initially continuous cliffs, tentatively regarded as fault scarps, that have been exposed by the withdrawal of protective ice. Couloirs or consequent gullies first make their

[18] Shown in some of the Lindbergh photographs (A. M. Lindbergh, Flying Around the North Atlantic, *Nat. Geog. Mag.*, 66, pp. 261-337, especially p. 286, 1934).

[19] Griffith Taylor, Physiography and Glacial Geology of East Antarctica, *Geog. Jour.*, 44, pp. 365-82, 452-67, 553-71, 1914.

appearance as a result of physical weathering, snowdrift accumulation, and removal of fine debris by melt-water streams. These chimneys are enlarged to half-funnel forms by nivation and, as the snowdrifts become hanging glaciers, the process is continued by head-wall sapping until the perfect corrie form is assumed.

Not only are there these perched corries on the scarps, however, but valley-head cirques of typical form are found at the heads of typical troughs, and the origin of the troughs as well as the cirques has been attributed by Taylor to a similar process of head-wall sapping. This hypothesis he has favoured in preference to that of deepening or other modification of normal valleys by glacial corrasion, for it would be difficult to postulate climatic conditions in this region subsequent to tectonic initiation of its landscape forms (broad benches separated by scarps) such as would permit of the normal dissection of benches by rain and rivers, especially as other benches in the vicinity appear to have enjoyed perfect protection beneath a snow-and-ice cover.

One broad bench in particular is now trenched by typically glaciated troughs entered at the sides by hanging tributary valleys and bordered by corries of perfect form. Only locally are such glacier cirque-and-trough forms modified or obliterated owing to invasion by large overflow streams of ice from the Antarctic interior (outlet glaciers), of which the Ferrar Glacier is one instance. Davis Valley, considered as a typical example of the cirque-and-trough forms that dissect the upland, originated, according to Taylor's theory, as a corrie on the scarp of the bench across which it has since gnawed its way back for miles by continued head-wall sapping until now it is a trough "3000 ft. deep, 8 miles long, and a mile or so broad". It is occupied for only half its length by a glacier, but Taylor has suggested that this is the "actual agent" undiminished which "burrowed its way westward by thaw-and-freeze action" so as to excavate the whole trough. Such portions of the partly dissected upland bench as survive here between the valleys of which Davis Valley is the type are of small relief. They are covered by a thin protective layer of stagnant ice which may be regarded as an extension of the Antarctic ice sheet.

Headward Glacial Erosion

The explanation of the origin of some glacier-trough valleys of considerable dimensions by headward glacial erosion instead of by glacial corrasion is attractive as a working hypothesis. It was forced on Taylor by the necessity in a particular case of finding an explanation of the dissection of an upland by glacial erosion alone, working on an initial landscape of tectonic origin instead of as a climatic accident modifying forms of normal erosion. A somewhat similar suggestion had previously been made by Helland in Norway[20] and later by Willard D. Johnson regarding the glacial sculpture of the Californian High Sierras when he wrote: "It was obvious, postulating recession, that the canyons of this summit region were independent in their courses, and had developed independently of the initial upland drainage plan."[21] This implies development of entire glacial troughs—not cirques only—by headward erosion.

It would be ridiculous, in view of the very considerable survival of preglacial landscapes in such regions, to argue that the great glaciated valleys of the European Alps or of the New Zealand Alps, to mention only two such regions of mountain glaciation, are not in the main troughs developed by corrasion along the lines of pre-existing normal valleys. Even in the Sierra Nevada Johnson's suggestion that glacial forms, both cirques and troughs, are independent of preglacial forms is unsupported, and in Norway the doctrine of the existence of rejuvenated preglacial valleys on the sites of present-day fiords seems well-founded. As regards Antarctica and the Fiordland district of south-western New Zealand, however, nothing is known with certainty of the existence of preglacial valleys; and for such regions Taylor's hypothesis of headward glacial erosion must be treated with respect.

The hypothesis does not require sapping by freeze-and-thaw to account for all the features of all the present-day valleys that were initiated by glacial headward erosion. The valleys have come to be occupied by glacier tongues, which must have abraded and

[20] A. Helland, Om Botner og Sækkedale . . . , *Geol. Fören. Förh. Stockholm*, 2, 1875.

[21] W. D. Johnson, The Profile of Maturity in Alpine Glacial Erosion, *Jour. Geol.*, 12, p. 572, 1904.

modified the features of their floors and perhaps their walls—possibly in some cases to a very great extent, though in others only in a minor degree. According to Taylor's "palimpsest" theory[22] the Ferrar Glacier Valley in Antarctica has been so modified that original features of a cirque stairway, forming the initial notch through which this outlet glacier apparently took its course, have been almost destroyed.

Initial and Infantile Forms of Cirques

Sapping theories of cirque development are not difficult to appreciate in so far as they are applied to the enlargement of amphitheatres already in existence; but the initiation of the amphitheatre generally presents a separate problem. Isolated corries and amphitheatre-shaped valley heads cannot all have resulted from enlargement of one particular type of initial niche; but in most cases some hollow or dimple in the preglacial landscape no doubt determined the site of a future cirque.

An observed rapid development of funnel-shaped ravines by active mechanical weathering under Arctic and sub-Arctic conditions on oversteepened slopes (producing "rasskars"[23]) suggests that many such funnels, which were no doubt developed in interglacial epochs, have later been occupied and enlarged by corrie glaciers.

It is rather commonly assumed that the glaciers which have excavated cirques have occupied normal preglacial valley heads.[24] It is very doubtful, however, whether such a generalisation covers all cases. The explanation seems to fit the case of many valley-head cirques, those situated where youthful preglacial valley heads have dissected an upland to forms of early maturity, producing normally eroded mountains. Snowfields have collected in the funnel-shaped valley heads and have become névés with sufficient output of glacier ice to abrade, scoop out, and convert the collecting areas into infantile cirques. Some observations are taken to indicate

[22] Griffith Taylor, *loc. cit.* (19).

[23] H. W. Ahlmann, Geomorphological Studies in Norway, *Geografiska Annaler*, 1, p. 215, 1919; see also above (pp. 198-9) and G. Taylor, *loc. cit.* (19).

[24] "Headwater basins of torrents" (E. de Martonne, L'Erosion glaciaire et la formation des vallées alpines, *Ann. de Géogr.*, 19, p. 313, 1910); see also E. Richter, *loc. cit.* (10); S. Passarge, *Physiologische Morphologie*, p. 57, 1912; F. Nussbaum, Beobachtungen über Gletschererosion . . . , *C-R. XV Internat. Géogr. Congr.*, 2, p. 66, 1938.

that when a thickness of 125 feet of névé accumulates on a twelve per cent slope glacier movement becomes possible,[25] though this may be an underestimate of the thickness required.[26] Especially where several headwater tributaries have converged, the combined collecting areas thus provided might become the infantile shallow half-basins converted later by sapping into typical large cirques. In mountain regions cirques may be initiated in a similar way in small side valleys also, being left hanging or perched on valley sides when main valleys are deepened or broadened.

Nivation

The erosive work of snowdrifts ("nivation") has been investigated especially with the purpose of finding an explanation of initial cirque forms. On the ice-worn but not deeply abraded surface of Lapland the sites of "more or less persistent snowdrifts" of the present day on hillsides "have become distinct niches in which the characteristic 'armchair' form of the incipient cirque is already apparent."[27] On preserved preglacial slopes on the Big Horn Mountains Matthes "has demonstrated that the snowbanks without movement steadily deepen the often slight depressions in which they lie, a process which he has called 'nivation'—excessive frost-work about the receding margins of the drifts during the summer season. The ground being continually moist in this belt due to the melting of the snow, the water penetrates into every crevice of the underlying rock, so that it is rent during the nightly freezing. Rock material thus broken up and eventually comminuted is removed by the rills of water from the melting snow. . . . The original depression is deepened, and, if upon a steep slope, its wall becomes recessed. The occupation of a V-shaped valley by snow . . . tends . . . to transform it into one of U-section. . . . All gradations from nivated to glaciated forms are to be found in the Big Horn Range."[28]

[25] F. E. Matthes, Glacial Sculpture of the Big Horn Mountains, *U.S. Geol. Surv. Ann. Rep.*, 21, p. 190, 1900.

[26] W. H. Hobbs, *Characteristics of Existing Glaciers*, p. 22, 1911.

[27] W. H. Hobbs, *loc. cit.* (26), p. 21.

[28] W. H. Hobbs, *loc. cit.* (26), pp. 19-20. The nivation hypothesis was formulated by F. E. Matthes (*loc. cit.* (25)), and has been adopted by B. Högbom (Ueber die geologische Bedeutung des Frostes, *Bull. Geol. Inst. Univ. Upsala*, 12, pp. 257-398, 1914) and many others.

On gentle slopes of nearly level uplands and on broadly subdued land surfaces in general, into which many deep armchair cirques or corries have been bitten, preglacial valley forms appear generally to have been too shallow to accommodate glaciers, and the nivation hypothesis has been appealed to to afford an explanation of the conversion of shallow dimples holding snow patches into infantile niches later developing into cirques. It might be argued that no examples can exist of such features in course of development; that those initial hollows capable of collecting snow must have been all converted into cirques in the Glacial Period. During epochs of intense refrigeration, however, these uplands were covered and protected, no doubt, by continuous snowfields at temperatures too low for nivation and sapping by processes involving *thaw* and freeze. In Iceland, moreover, nivation may now be observed in progress on quite new constructional surfaces of volcanic origin.

The rôle of nivation in producing incipient and even well-hollowed cirque forms—broad dimples on surfaces of gentle slope and also deepened niches in steep slopes—has been found to be of greater importance than merely the preparation of initial hollows for further excavation into true glacial cirques. In the south-west of England (West Somerset), for example, existing hillside niches ("coombes") have been ascribed to a nivation process. "They appear to have been formed, at a time when the climate was more rigorous than at present, as a result of the daily melting of the margin of the snow covering the hilltops and the freezing at night of the water that trickled down the slopes."[29]

Very extensive highland surfaces in North America that have not been glaciated have been dimpled to the extent that "nivation cirques", so termed by Russell,[30] are now among the chief elements of their relief. These, together with "altiplanation terraces"[31] or "solifluction benches",[32] to a great extent take the place of a graded system of valleys of an old or late mature surface that would be

[29] J. W. Evans, *Proc. Geol. Assoc.*, 24, pp. 251-252, 1913; *ibid.*, 25, pp. 100, 103, 1914; *Geog. Jour.*, 44, p. 569, 1914.

[30] R. J. Russell, Alpine Land Forms of Western United States, *Bull. Geol. Soc. Am.*, 44, pp. 927-950, 1933.

[31] H. M. Eakin, The Yukon-Koyukuk Region, Alaska, *U.S. Geol. Surv. Bull.*, 631, pp. 78-79, 1916.

[32] R. J. Russell, *loc. cit.* (28), p. 929.

found on extensive peneplain remnants at lower levels. These benches result from solifluction, being produced as further material thus streaming in broad, water-saturated sheets down gentle slopes from higher ground at the rear has been banked up against frontal ramparts of coarser blocks that remain after water and the finer debris have been drained out of the flowing waste-layer. In some cases at least the subsoil under streaming solifluction sheets has been permanently frozen.

Nivation cirques also are products of climates of the tundra type, in which very low evaporation, together with sufficient precipitation, insures continued water-saturation of the ground and daily alternation of freeze and thaw occurs at the surface for more than a third of the year.[33] They vary in form according to the steepness of the slope on which they are developed, being mere shallow dimples on gentle slopes (where, however, they may occupy from half to nearly the whole surface), but on steeper surfaces assuming forms that "might readily be mistaken for large glacial cirques" (Russell). The distinction from glacial cirques is made in such cases by noting the complete absence of true moraines—as distinguished from talus heaps and ridges formed along the fronts of steep snow slopes—and of a hollowed or glacially worn floor.[34] It is noteworthy in this connection, however, that Bowman[35] attributes much of the work of excavation of nivation cirques in the Andes to bodily sliding of snowdrifts, and the distinction between nivation hollows and glacial cirques tends to break down when the transition from snow to firn and ice is taken into account.

Recent studies made in Iceland by Lewis[36] and in Spitsbergen by McCabe[37] have, however, confirmed the observations of Matthes and do not support the conclusions of Bowman. These observers have found also that the freeze-and-thaw process operates in summer not only at the margin of a snow patch but also beneath the snow, where, owing to abundance of melt-water, it is more effective than

[33] R. J. Russell, *loc. cit.* (30), p. 939.

[34] W. E. Ekblaw, The Importance of Nivation . . . in Northern Greenland, *Proc. Nat. Acad. Sci.*, 4, pp. 288-293, 1918.

[35] I. Bowman, *The Andes of Southern Peru,* pp. 285-94, New York: 1916.

[36] W. V. Lewis, Snow-patch Erosion in Iceland, *Geog. Jour.*, 94, pp. 153-161, 1939.

[37] L. H. McCabe, Nivation and Corrie Erosion in West Spitsbergen, *Geog. Jour.*, 94, pp. 447-465, 1939.

on bare ground. They have also observed the removal of frost-comminuted debris by water which trickles under snow patches.

The nivation process is rapid in its action, according to all observers, and so some glaciated forms have been considerably modified by nivation in the postglacial epoch.[38] Thus may be explained some cases of scalloping of crest-lines of cirques by rows of minor cirques or niches, to which reference has already been made (p. 184; Pl. XXV, 2).

Flutings in some cirque rims have been attributed by Lawson[39] to postglacial snow-slides, however; and more recently Matthes[40] has described some distinct and characteristic flutings on cirque walls in the Californian High Sierras, which he calls "snow chutes" or "avalanche chutes", terms equivalent to the French *cannelures,* applied by Allix, and attributes to erosion by avalanches of snow and rock debris.

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[38] R. J. Russell, *loc. cit.* (30), p. 936.

[39] A. C. Lawson, The Geomorphogeny of the Upper Kern Basin, *Univ. Cal. Publ., Bull. Dep. Geol.,* 3, p. 367, 1904.

[40] F. E. Matthes, Avalanche Sculpture in the Sierra Nevada of California, *Internat. Soc. Hydrol. Bull.,* 23, pp. 631-637, 1938.

CHAPTER XVI

Glacial Troughs

THE ACTUAL channel occupied by a glacier tongue, which becomes an axial or inner valley or "trough,"[1] when the glacier melts away, is almost invariably shaped by the glacier itself to the form of a groove or trench (Pl. XXX, 2). There are cases where the process has been interfered with or arrested at some stage of incompleteness, but in the completed form the cross profile is either a simple U or a flatter-floored trough form, but in the latter case with some concavity of the lower sidewalls, which perhaps broaden to a catenary curve (Pl. XXXI, 1 and 2).

According to de Martonne[2] the glacier "like all fluids, tends to give its channel a semicircular section." Whether a perfect curve or not the profile is generally almost continuously concave at the bottom, at least in all but the largest troughs (Fig. 74, and Pl. XXXI, 2).

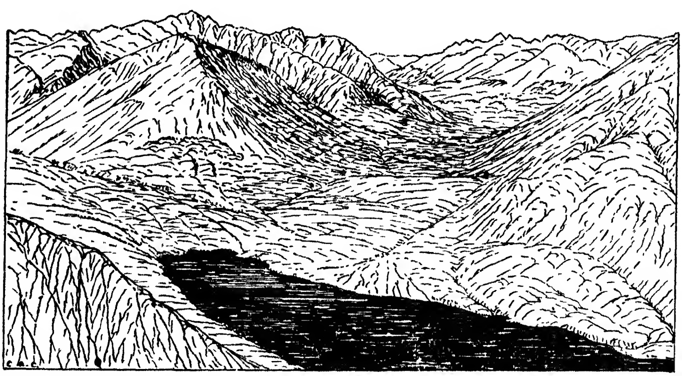

Fig. 74. The U-shaped trough of the Upper Mararoa Valley, New Zealand (above Mavora Lake). (Drawn from a photograph by C. O. Hutton.)

[1] A. Penck's empirical term *Taltrog* (*Morphologie der Erdoberfläche,* 2, p. 66, 1894) was adopted by E. Richter (Geomorphologische Untersuchungen in den Hochalpen, *Pet. Mitt. Ergänz.,* 132, p. 49, 1900) for an abandoned glacier channel of U-form. Penck's ideal *Taltrog,* however, has a flat floor which meets convex side slopes nearly at right angles.

[2] E. de Martonne, Quelques données nouvelles sur la jeunesse du relief préglaciaire dans les Alpes, *Rec. de trav. Cvijic',* p. 135, 1924.

Some of the very large troughs which are now occupied by fiords and piedmont lakes—e.g. Alaskan fiords[3] and the Lake Wakatipu trough, in New Zealand[4]—have floors that are flat across the greater part of their width. Flat floors in many abandoned troughs, however, such as those now occupied by the Canterbury rivers flowing from the New Zealand Alps, are aggraded plains the alluvium of which deeply buries the bedrock floors so that there is now no visible indication of their form.

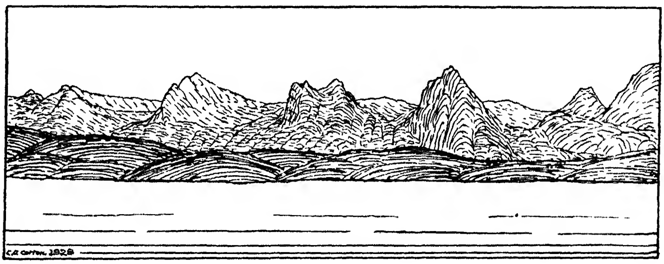

Fig. 75. U-shaped outlet-glacier channels separating tinds, Seven Sisters, Helgeland, Norway. The island in the foreground is part of the "strandflat."

The U-form, concave rockfloor profile is seen in many cirques in their frontal parts, which have been shaped by glacial corrasion, in the mouths of sharply cut off hanging valleys (e.g., Figs. 80-86), and, perhaps best of all, in the troughs of former outlet glaciers by way of which the ice of continental glaciers has spilled over plateau edges. Such, for example, are the gaps between the residual peaks ("tinds") known as the Seven Sisters, on the coast of Norway (Fig. 75). No description fits this profile curve better than the well established expression "U-shaped," though "catenary" is admissible if not too strictly defined.

Accumulation of valley-side talus cones and steep alluvial fans masks the lower valley-side concavity (or angle?) in many troughs; but it is clear in most cases that observed U forms are not a result of the masking of a sharp re-entering angle such as is present in the conventional *Taltrog* of Penck,[5] a form sometimes accepted as

[3] R. S. Tarr, *College Physiography*, Figs. 154-6, 1914.
[4] K. Lucas, A Bathymetrical Survey of the Lakes of New Zealand, *Geog. Jour.*, 23, pp. 645-660, 744-760, 1904.
[5] A. Penck, *loc. cit.* (1).

"the typical cross-profile of a glaciated valley."[6] Obviously, however, there is considerable variability in the transition curve between the steepest part of the wall and the axial portion of the floor, and cross profiles must vary accordingly.

In many instances it appears that only a moderate amount of modification of a preglacial valley has been required to provide a glacier with a suitable channel, and generally in such cases broad catenary forms are found. Undoubtedly many such valley forms in regions not heavily glaciated indicate that glaciers have there occupied valleys already broadly opened. The fact that wide-open troughs with moderate side slopes occur mainly in terrains of easily eroded rocks need not lead necessarily to the conclusion that in such terrains glacier ice has found it easier to cut broad rather than deep channels, but indicates in many cases the probability that the preglacial valleys had been broadly opened on these terrains, and that the ice thus found wide channels already available. Where, on the other hand, preglacial valleys narrowed to become gorges across resistant outcrops the infant glaciers had to squeeze through these, and their restricted streams gouged out for themselves narrow, steeper-walled—that is, U-shaped—troughs (Pl. XXXII, 1). The effects under heavy glaciation, where there has been deep excavation, may be very different, however.

If it be assumed a fact that the inner trough in a valley formerly occupied by a glacier has been at least shaped as a channel for itself by the ice stream, we find opposed views current on the question of whether glacier-tongue erosion is almost wholly vertical corrasion or is to an important extent lateral. (It is a separate question whether lateral corrasion has been assisted by lateral sapping of a similar kind to the head-wall sapping that enlarges cirques.) A trough or U-form valley may be derived on the hypothesis of either vertical or lateral corrasion from a preglacial V-form profile, or, for that matter, from a broadly mature preglacial valley, if the trough be a large one. A trough or glacier channel of relatively small dimensions as compared with a major valley form containing it is best explained by vertical corrasion if it may be assumed that the preglacial valley was broadly open and mature.

[6] Wooldridge and Morgan, *The Physical Basis of Geography*, p. 369 and Fig. 227, 1937.

If, however, the preglacial valley was rejuvenated, and thus deepened along the axial line, just prior to its occupation by ice, it required little or no glacial deepening, and the enlargement and straightening of the inner valley of the preglacial valley-in-valley form may be all that need be ascribed to glacial erosion.

According to Penck's hypothesis of overdeepening (p. 163) the glaciated troughs of the European Alps are derived from preglacial mature valleys by the process of vertical glacial corrasion.[7] De Martonne's rival hypothesis in its simplest form demands the presence of V-shaped inner valleys of rejuvenation, which, when occupied by infant glaciers, have been enlarged by them to become U-shaped troughs without the glaciers being required to do much vertical cutting.[8] Besides the U form of the glacier channel there are numerous other features of the floors and sides of glaciated valleys by means of which theories of their origin may be tested, and the hypotheses of overdeepening and lateral enlargement must be borne in mind when they are examined.

Erosion Under Thick Glaciers

While there is room for some difference of opinion in many cases as to the depth of glacial excavation, it is quite obvious that vertical corrasion under ice streams has proceeded in some instances to depths of thousands of feet. Notable examples are to be found in the deeper parts of the floors of fiords and piedmont lakes (Chapter XX). For such excavation mechanical corrasion by rock fragments firmly held in the sole of a heavy and rapidly-moving ice stream may be called upon to do much of the work. Simple plucking may play a part also, however, and the freeze-and-thaw process (as noted already in Chapter XIV) perhaps co-operates with it, making fragments available for easy plucking by disintegrating the subglacial rock surface; for the temperature is near, and possibly oscillates about, the melting point at the bottom of the ice stream in all thick glaciers, even in regions of very low surface temperature (p. 130).

[7] A. Penck, Die Uebertiefung der Alpentäler, *Verh. VII Intern. Geog. Kongr.*, 2, pp. 232-240, Berlin: 1900; Glacial Features in the Surface of the Alps, *Jour. Geol.*, 13, pp. 1-19, 1905.

[8] E. de Martonne, L'érosion glaciaire et la formation des vallées alpines, *Ann. de Géog.*, 19, pp. 289-317; 20, pp. 1-29, 1910; also *loc cit.* (2).

Postglacial Modification of the Trough Form

The side slopes of glacial channels that are no longer occupied by ice have been subject to postglacial modification by weathering and water erosion. Side slopes while they were in contact with ice, though subject to ice abrasion and lateral glacial corrasion by freeze and thaw under the glaciers, were protected from direct atmospheric weathering.

After the glaciers have melted away, the gentler side slopes so exposed have been subject to gullying and dissection. Dissection of trough-side slopes by ravines is far advanced in many glaciated regions, especially in terrains which are rapidly disintegrated by weathering. This is notably the case, for example, in the greywacke ranges of the eastern side of the New Zealand Alps[9] and in the

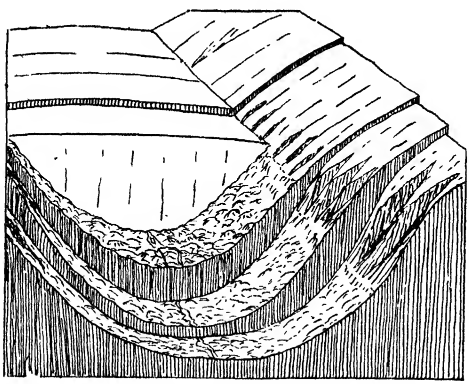

Fig. 76. A glacier progressively deepens its trough and abandons the upper side walls to normal erosion. (Based on a diagram by W. M. Davis.)

schist mountains farther south. Dissection has, indeed, already wrought considerable changes in the appearance of the side walls of some valleys in which glaciers still linger, and it is reasonable to regard some trough-side ravining as having been done during the latter part of the last glacial epoch, when glaciers were shrinking. Dissection of the upper walls of troughs may possibly even result from their abandonment to normal erosion as glaciers entrench

[9] R. Speight, Note on the Hanging Valleys of the Upper Rangitata Valley, *Trans. N.Z. Inst.*, 54, pp. 90-98, 1923.

themselves more and more deeply in abraded grooves by progressive trough-deepening (Fig. 76).[10]

One effect of superglacial trough-side erosion has been to produce the Y valleys[11] of some present-day landscapes. They take this Y form when open V-shaped valleys of superglacial origin (or in other cases preglacial—p. 225) on the upper part of the side of a catenary trough are continued downward in the stem of the Y by narrower postglacial ravines. Fine examples of such valleys are present along both sides of the broad trough of Lake Wakatipu (Pl. XXXII, 2).

Postglacial Ravines and Screes

Steep, rocky trough-side slopes and also the head walls of cirques are subject to intense weathering when exposed to the atmosphere in a postglacial cycle. This decreases their declivities by back-wearing above and talus accumulation below. Eventually normal grading of such slopes must ensue, but on most terrains they are still very young. They are fringed by aprons of talus in some cases still almost negligible in amount, but in others very voluminous—as, for example, in the case of the well-known "Screes" bordering the English lake Wastwater. Absence of visible talus along the side walls of some troughs is due to the burial of screes under gravels which cover the floors of the troughs as a result of postglacial aggradation.

In Norway some great rock falls from trough sides have taken place even in historic times.[12] The scars left by these are very conspicuous funnel-like forms breaking the continuity of steep upper slopes. They are included among the forms termed "rasskars".[13]

Avalanche Ramparts and Tarns

In some glaciated mountain regions which have still a high winter snowfall much snow accumulates on high-level benches and descends thence into the valleys as avalanches, so that aprons of

[10] W. M. Davis, *Die erklärende Beschreibung der Landformen*, p. 412, 1912.

[11] W. M. Davis so described these forms, orally, when in their presence at Lake Wakatipu, New Zealand, in 1914. Probably there is a reference to Y valleys somewhere in his writings.

[12] A great rock fall occurred in 1908 in Norangerdal. (H. W. Ahlmann, Geomorphological Studies in Norway, *Geografiska Annaler*, 1, p. 125, 1919.)

[13] H. W. Ahlmann, *loc. cit.* (12), pp. 124-127.

avalanche snow are present for a great part of the year along the bases of steep trough sides. Falling rock debris and that swept down by later avalanches is thus prevented from accumulating at the actual foot of the slope but glissades forward instead over the snow apron to build a rampart along its margin. When the avalanche snow melts away in the summer the ramparts enclose avalanche tarns. Such avalanche-built features are common along the sides of the deep troughs in the Fiordland district of New Zealand.[14]

A similar glissading of rocks across small cirque glaciers has been described, the result of which is to build pseudo-morainic ridges.[15]

Non-glaciated Trough-form Valleys

The discussion of U-form glacial troughs is incomplete without an examination of the possibility of development of similar transverse valley profiles without the agency of glacial abrasion. The broad U or catenary form of profile may be developed in a valley, it has been suggested, by processes short of actual glacial abrasion under tundra or arctic conditions of climate. Nivation, as Matthes[16] and others have shown, may open out small valleys from V form to U form. According to the view of Russell, moreover, "frost action and solifluction . . . act with such rapidity that even though streams of ice did occupy certain . . . valleys in the past, their present U section may be quite unrelated to that fact."[17]

Taylor[18] earlier outlined a frost-erosion hypothesis, which he applied in an attempt to explain the U-shaped profiles of large valleys in Antarctica without recourse to a theory of extensive glacial corrasion, though all the valleys there are or have been occupied by ice, stagnant glaciers still exist in parts of valleys at present nearly ice-free, and there is a possibility that glacial corrasion,

[14] P. Marshall, *Geology of New Zealand*, p. 44 and Fig. 19, 1912.

[15] O. D. von Engeln, Palisade Glacier of the High Sierra of California, *Bull. Geol. Soc. Am.*, 44, p. 584, 1933.

[16] F. E. Matthes, Glacial Sculpture of the Big Horn Mountains, Wyoming, *U.S. Geol. Surv. Ann. Rep.*, 21, pp. 167-190, 1900.

[17] R. J. Russell, Alpine Landforms of Western United States, *Bull. Geol. Soc. Am.*, 44, p. 947, 1933.

[18] Griffith Taylor, Physiography and Glacial Geology of East Antarctica, *Geog. Jour.*, 44, pp. 365-82, 452-67, 553-71, 1914.

though now at a standstill in these valleys, has been active in the distant past when the climate was less *cold* and dry. The frost hypothesis, Taylor has suggested, may have application to other regions where there is a possibility of normal valleys having been converted into catenary troughs while they contained thin, non-eroding (perhaps stagnant) glaciers.

The rock floors of those Antarctic valleys which contain only stagnant glacier remnants, or "ice slabs", have not a mammillated surface such as would indicate that they had been recently excavated by glacial abrasion, and the valley sides are similarly smooth. A veneer of rock debris on exposed parts of the valley floor consists, at least in part, of ground moraine left by the former glacier; but on the valley-side slopes the thin layer of rock fragments present has been found to consist only of the debris of mechanical weathering broken by frost action to "a fine gravel". Over large areas this lies on a smooth bedrock slope with a remarkably uniform inclination of thirty-three degrees, which is near the angle of repose of the gravelly veneer. (Owing to the very low temperature there are no water streams to cut gullies or to remove or sort the debris.) The valley side, if reduced to this slope by weathering, is homologous with the slopes of the fronts of rainless-desert mountains developed as deduced by Lawson.[18a] Taylor has not proposed a theory of progressive back-wearing or retreat of such slopes, but he has pointed out that frost action cannot reduce the slope to a gentler declivity, as debris accumulating so as to form more than a thin layer in transit downhill would be preservative. Disposal of such rock debris from the side wall as reaches the foot of the slope may be the task of a summer melt-water stream in the moat opened by ice wastage between the rock wall and the stagnant glacier on the floor; but presumably a more active glacier if it were present in the bottom of the valley would be able to remove it more effectively and co-operate with a back-wearing process.

The theory of trough development by superglacial weathering of the walls, in which frost action is a dominant process, has been

[18a] A. C. Lawson, The Epigene Profiles of the Desert, *Univ. Cal. Publ., Bull. Dep. Geol.*, 9 (3), pp. 23-25, 1915.

independently advocated by Sölch,[19] who appears to have overlooked Taylor's hypothesis. Sölch finds time available in interglacial epochs for the weathering back of valley-sides (mainly by frost action) so as to develop broad U forms in Alpine valleys, though these have been later occupied by glaciers. If it appeared to be true, as Sölch maintains, that glaciers are conservative—that is, that they are relatively less efficient than back-weathering as trough-makers—the more frequent and prolonged exposure of upper parts of valley-side slopes to the atmosphere would account better for the upper-wall convexity in the ideal trough as figured by Penck (p. 206) than for the lower concavity of catenary-trough profiles to which the theory is applied.

Another agency, the action of which above ice-level has been suggested, is aeolian abrasion of rock walls. As a minor factor contributing to the enlargement of valleys that contain glaciers something resembling sand-blast erosion sometimes operates, as is proved by the discovery of evidence of aeolian abrasion on rock outcrops and boulders in some glaciated valleys of the Sierra Nevada of California.[20] Since attention has been drawn to the great hardness of ice at low temperatures[21] it has been suggested that these abrasive effects have been produced not by sand but by a "snow-blast" action during very cold gales.[22]

River-made Troughs

Without invoking the agency of special processes for their development one may find very numerous valleys with broadly-opened, almost typical trough profiles among purely river-made landforms. Valleys with spurless side walls or with faceted ends on the valley-side spurs are common in non-glaciated regions of moderate to strong relief wherever valley-development has reached that stage of maturity at which formerly interlocking spurs from the valley sides have been shorn back by lateral river corrasion to

[19] J. Sölch, Fluss- und Eiswerk in den Alpen zwischen Ötztal und St. Gotthard, *Pet. Mitt. Ergänzungshefte*, 219, 220, 1935; Trogprofile und Trogstufen, *CR. Congr. Internat. Géog. Amsterdam*, 2, pp. 191-197, 1938.

[20] E. Blackwelder, Sand-blast Action in Relation to the Glaciers of the Sierra Nevada, *Jour. Geol.*, 37, pp. 256-260, 1929.

[21] C. Teichert, *Am. Jour. Sci.*, 237, pp. 146-148, 1939.

[22] E. Blackwelder, *Am. Jour. Sci.*, 238, pp. 61-62, 1940.

become lines of bluffs[23] (Pl. XXXIII, 1). Apart from absence of collateral evidence of glacial occupation (such as morainic accumulations, rock-basin lakes, and "glaciated" rock outcrops in the valley) such U-form normal valleys are distinguished from glacial troughs mainly by the absence of discordant tributary junctions.

The discordant junctions of early youth have long ago been eliminated, and discordance of level at the junctions of tributaries with a main river in a large, open, river-cut valley can occur only very exceptionally. When one is present it is either very obviously related to some striking heterogeneity in the terrain or to some local accident of a very special nature which has led to rapid rejuvenation in the main valley. Examples of such a case have been noted, however, by Chamberlin[24] in the upper Ohio and upper Missouri valleys. These rivers, on account of receiving "great accessions of water" due to an exceptional cause have "broadened and deepened the main channels out of all concordance with their tributaries." So "these as they approach the main valley . . . rush down through new gorges."[25] The attention devoted to these features is an indication that Chamberlin regarded them as very exceptional.

[23] See C. A. Cotton, *Landscape*, second edition, p. 170, Fig. 144.

[24] T. C. Chamberlin, Further Studies of the Drainage Features of the Upper Ohio Basin, *Am. Jour. Sci.*, 47, pp. 261-262, 1894.

[25] T.C.C., *Jour. Geol.*, 8, p. 572, 1900.

CHAPTER XVII

Glacial Hanging Valleys

In contrast with the forms usually found in open-floored river-cut valleys an almost invariable peculiarity of U-shaped and trough-shaped valleys of true glacial origin is discordance of the junctions of tributaries, which commonly enter the main river from the mouths of conspicuously "hanging" side valleys.

The value of the evidence afforded by hanging valleys as proof of glacial excavation of main valleys has been discounted by some "water erosionists" who have attempted to explain the peculiar features of glaciated landscapes as of normal (non-glacial) origin. They have maintained that hanging valleys themselves are normal features and have drawn attention to certain examples of discordance in valley systems which all will agree are river-made.

Notwithstanding efforts to minimise the importance of occasional exceptions to Playfair's law of accordant junctions as applied to the valleys of normal landscapes,[1] few geomorphologists fail to recognise an important, even if usually short-lived, stage of the Davisian normal cycle in which discordance of junctions is quite generally present.[2] It has not been the fortune of every observer, however, to become familiarly acquainted in the field with conspicuous examples of discordant normal junctions.[3]

It seems permissible, and indeed necessary, therefore, to refer in a brief digression to the features of young normal valleys which are generally associated with the presence of discordant tributary junctions. Only quite exceptionally, be it noted, has a rejuvenation of the main valley been the result of a flooding confined to it and of such a catastrophic nature as to enlarge it laterally as well as vertically (p. 215). Commonly the main valley, or at least the inner valley of a valley-in-valley arrangement which is due to the most

[1] See, for example, A. K. Lobeck, *Geomorphology,* p. 176, 1939.

[2] C. A. Cotton, *Landscape,* second edition, p. 47.

[3] One may, for this reason, freely forgive the misinterpretation of a diagram drawn by the author in illustration of such a feature and its astonishing adoption in a textbook as an example of a glacial landform. (Wooldridge and Morgan, *The Physical Basis of Geography,* Fig. 230, 1937.)

recent rejuvenation, is narrow and gorge-like and the width of its floor is little greater than sufficient to accommodate the channel of the river flowing in it (Fig. 77). Herein lies the most important distinction from those glacial valleys above which side-valley junctions commonly hang; for these are broad-floored troughs.

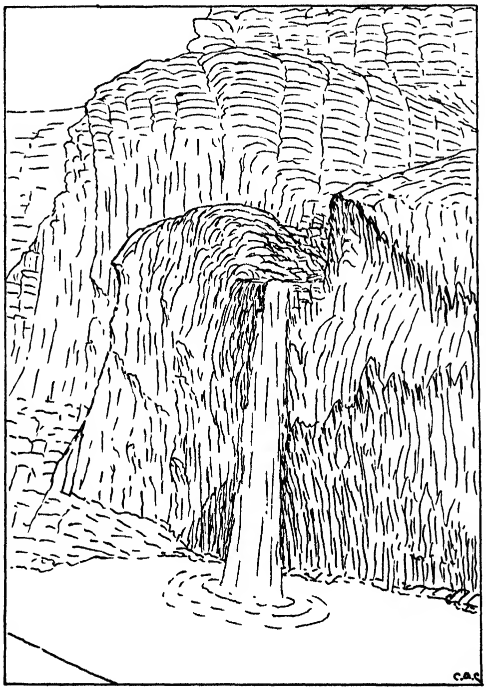

Fig. 77. Discordant junction in a normal valley, Havasu Canyon, Colorado River of the West. (Drawn from a photograph.)

Glacial Accordance and Discordance

In many glaciated regions an accordant[4] junction may be looked for only in the rare case where a valley forks into two branches of equal size—where, for example, in the Sawatch Range of the Rocky Mountains, in Colorado, "seven miles west of Twin Lakes, the valley of Lake Creek divides at the village of Everett into two

[4] "Accordant" is here applied in the usual geomorphic sense. An unfortunate misappropriation of "accordant" and "discordant" for the description of junctions of glacier tongues in which ice streams derived from secondaries do and do not commingle with the main has been made by Odell (see p. 131).

branch valleys of about equal size . . . Large branch glaciers must have united there."[5] Even in such a case there will be, more often than not, a step up into each of the branches, as may be seen in the Nærodal trough (Norway) at Stalheim (Fig. 77A).

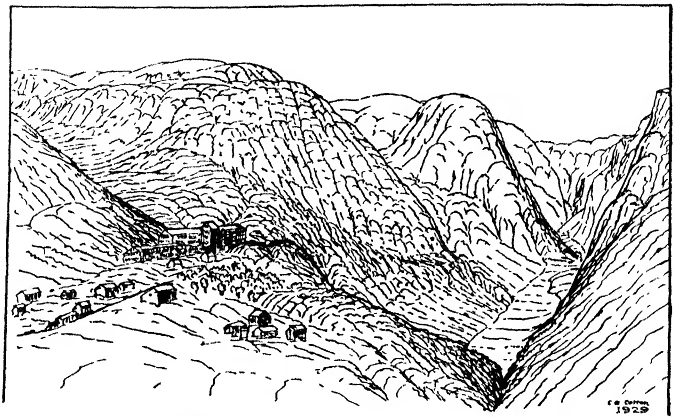

Fig. 77A. A composite sketch of the view down into Nærodal trough (right) from the hanging mouth of Opheim valley. At the left is the hanging mouth of Sivle valley. At Stalheim (foreground) glaciers from Opheim and Sivle valleys have joined forces; and overdeepening by the combined ice stream may be the main cause of the fiord-like trench form of Nærodal.

Absence of accordant side valleys is particularly noticeable in the deep glacial canyons, or "fiord valleys," of the Fiordland district in south-western New Zealand (Pl. XXXIII, 2) for the side walls of these canyons are commonly of such steepness as to be unscalable, and extend for many miles unbroken by any opening less than perhaps 3,000 feet above the floor. The diagram by W. M. Davis, reproduced as Fig. 78, gives an idea of the form, but shows side valleys larger and more deeply cut. The walls of the cirques at the valley heads of Fiordland are generally unscalable also, and though the floors, which are in most cases aggraded by postglacial water streams, are easily traversed there is only one way into and out of such a valley, even for Alpine climbers. The Clinton trough, which is relatively accessible, as it is followed from end to end by the overland walking track to Milford Sound (fiord), serves as an example of the Fiordland troughs. It is not in every respect a

[5] W. M. Davis, Glacial Erosion in the Sawatch Range, *Appalachia,* 10, p. 399, 1905.

typical example, however, for it is rather exceptional in that the wall of the cirque at its head is scalable, affording a pass (the result of some deepening due to glacial transfluence) to the valleys west of the main divide. In the case of the Homer Saddle "pass," which is another of the very rare gaps in the main divide, and which is on the route of the only road across Fiordland, the

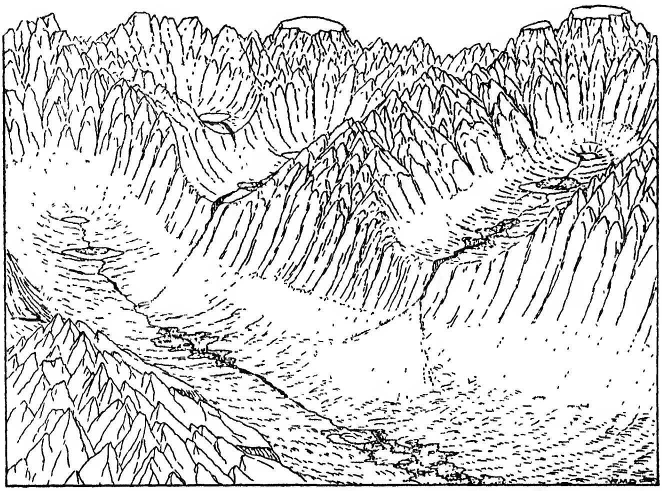

Fig. 78. A wall-sided, cirque-headed trough, bordered by hanging valleys. (After Davis.)

obstacle offered by the unscalable walls of the intersecting cirques at the gap is so great that the road cannot be taken over the col but must pass under it in a tunnel through the main divide of southern New Zealand (Pl. XXXIII, 2). Other fiord regions in Norway (Chapter XX), Spitsbergen (Pl. XXXIV, 1), Patagonia, Greenland, Labrador (Figs. 49A, 120), and Alaska (Figs. 79, 80) present similar features.

In all these regions high-hanging tributary junctions are conspicuous, resulting in the most striking scenic effects where hanging valleys perch on fiord walls (Fig. 79) and voluminous falls spout from them (Pls. XXII, 2; XLVII, 1; Fig. 84). Milford Sound, one of the New Zealand fiords, is flanked not only by two great waterfalls, which plunge from broad hanging-valley mouths some 500 feet high into the sea-water of the fiord, but also by two vast cirque-

Fig. 79. The Chilkoot trough wall, with hanging valleys opening at heights of 3,500 to 4,000 feet, Alaska. (After G. K. Gilbert.)

headed valleys (Pl. XXXIV, 2) opening at a smaller height above sea-level but still far above the floor of the immensely deep fiord; and farther inland, in one of the great fiord valleys that converge at the head of this fiord, the Sutherland Falls drop 1,904 feet to the valley floor from the rock rim of a hollow-floored hanging valley of cirque origin containing Lake Quill (Pl. XXIII, 1 and 2). In Lake Maggiore, a piedmont lake of the European Alps the close

Fig. 80. Hanging valley on Princess Royal Island, British Columbia, on the shore of Frazer Reach. (After G. K. Gilbert.)

genetic relationship of which to fiords is recognised, a hanging-valley junction submerged beneath the deep waters of the lake is present where the western arm joins that in the main (Ticino) trough,[6] and similar submerged hanging valleys have been mapped in Alaskan fiords.[7]

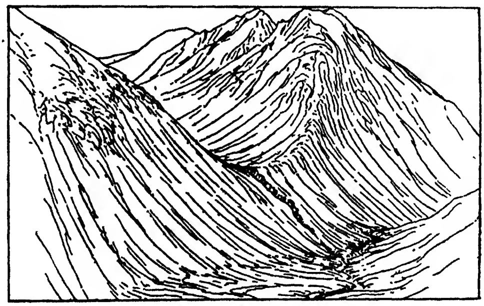

Fig. 81 A hanging valley, Guspistal, St. Gotthard Pass, Switzerland. (After W. M. Davis.)

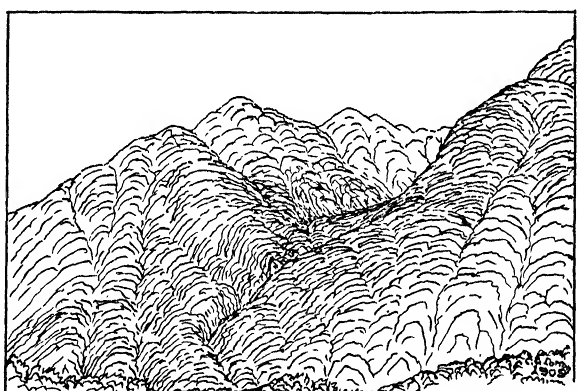

Fig. 82. Hanging valley bordering the Eglinton valley, New Zealand.

In the inland valleys of glaciated mountain regions hanging valleys are the rule, and there is no end to the examples that might be cited (Figs. 81-83, and Pl. XXXV, 1). A great many of these

[6] W. M. Davis, A Geographical Pilgrimage from Ireland to Italy, *Ann. Ass. Am. Geog.*, 2, p. 100, 1912.

[7] R. S. Tarr, *College Physiography,* Figs. 155, 227, 1914.

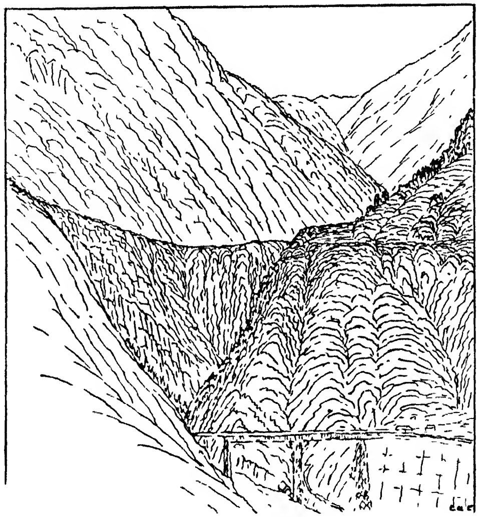

Fig. 83. The Maderanertal hanging valley, Amsteg, Switzerland, with a deeply-cut V gorge of post-glacial erosion.

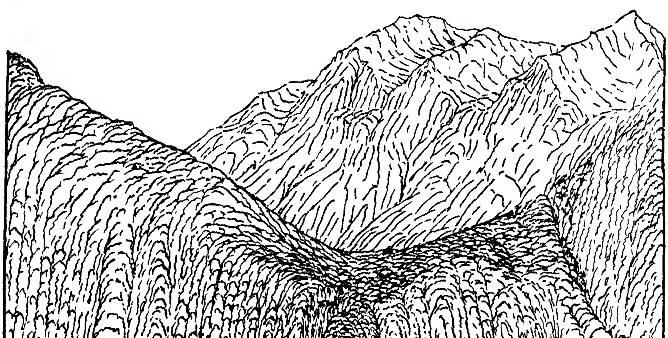

Fig. 84. Two-storied hanging valley, Bowen Falls, Milford Sound (fiord), New Zealand.

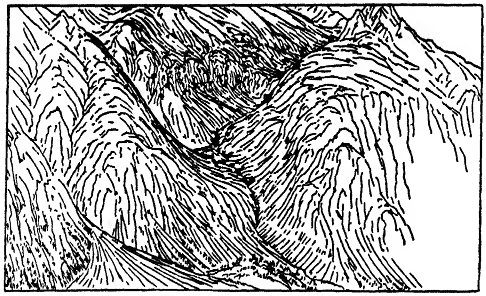

Fig. 85. Two-storied hanging valley, on the west side of the Aar valley (Haslital) near Handeck, Switzerland. (After W. M. Davis.)

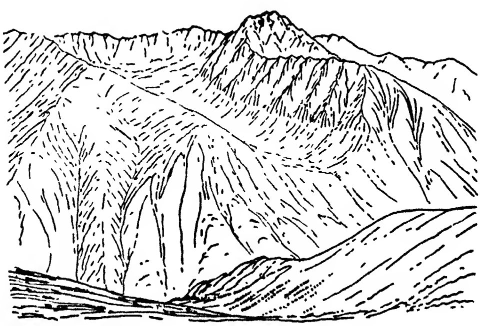

Fig. 86. Crystal Gulch, a hanging valley entering the deep trench of Lake Creek, Sawatch Range, Colorado. (After Davis.)

hanging valleys themselves carry the signs and scars of occupation and sculpture by glaciers, even to the extent of being entered by streams cascading from hanging side valleys or cirques (Figs, 78, 84-85) and have notably U-shaped or catenary cross profiles (Figs. 80-87). One glaciated hanging valley, in the strongly ice-worn Sawatch Range of the Rocky Mountains, in Colorado, which is about seven miles long and hangs at least 400 feet above the floor

of the main valley into which it opens, has been thus described by Davis:

> Crystal Gulch repeats, on a smaller scale, the trough-like channel, with broadly concave cross section, that is shown in the trunk glacier channel. Its sides become steep, though not vertical, and higher up are the superglacial spurs of less declivity rising to the mountain crests. The bed . . . shows a roughly scoured rock floor of gentle gradient, more or less cluttered over with rock slides and talus; and near the broad head of the gulch, where it is enclosed by a great amphi-

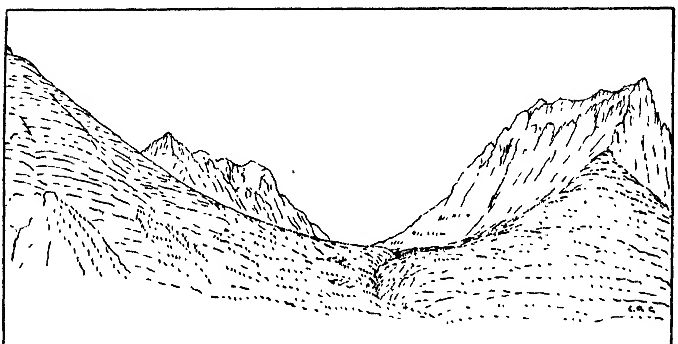

Fig. 87. Glaciated hanging valley with smooth catenary profile tributary to St. Mary Valley, Glacier National Park, Montana. (Drawn from a photograph.)

> theatre wall, rising for the most part in a ragged arête against the sky, the rocky bed is exceptionally uneven. But the most notable point in the relation of the side "gulch" to the main "valley" is the discordance in the level of their floors where they come together, for the gulch is a typical hanging valley . . . The abruptness of the change from the moderate gradient of the hanging valley to the steep side slope of the main channel was most remarkable. The outflowing creek had cut a small sluice in the side slope, and there it cascaded, half-hidden, to a fan, on which it sprawled down to Lake Creek; but the sluice was a trifling affair; it made no impression on the general view, in which the discordance of the lateral and main channel beds stood out so conspicuously.[8]

(See Fig. 86).

[8] W. M. Davis, *Appalachia,* 10, pp. 399-400, 1905.

Non-glaciated Hanging Valleys

In addition to such "glaciated" hanging valleys there are also many that are "non-glaciated." They present, that is to say, the cross profiles and other characteristics of normal valleys that have not been modified or even occupied by glaciers. The mere fact of the junction of non-glaciated tributary valleys with glaciated mains

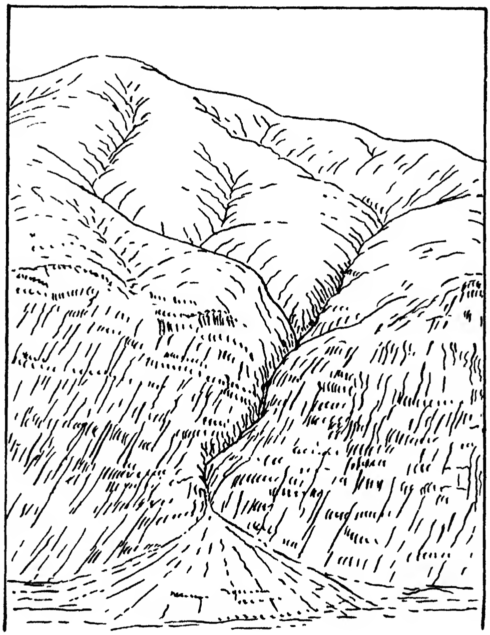

Fig. 88. Non-glaciated hanging side valley of the Dora Baltea valley, Italy. (After a sketch by W. M. Davis, redrawn.)

generally presents no problem. In the zone of alimentation a glacier tongue is fed by secondary glaciers occupying the branch valleys, but in the zone of ablation it is normally thrusting its way down a lower valley, the form of which it may modify, though in this part the side valleys are not filled by glaciers. Examples of valleys thus occupied in the Glacial Period are those of the Alpine piedmont in northern Italy, such as the Dora Baltea (Fig. 88) and

some now occupied by lakes, Lugano, for example.[9] Similar valleys in New Zealand are occupied by the lakes Wakatipu and Rotoiti (Fig. 89). (Compare the Y valleys of superglacial origin—p. 211.)

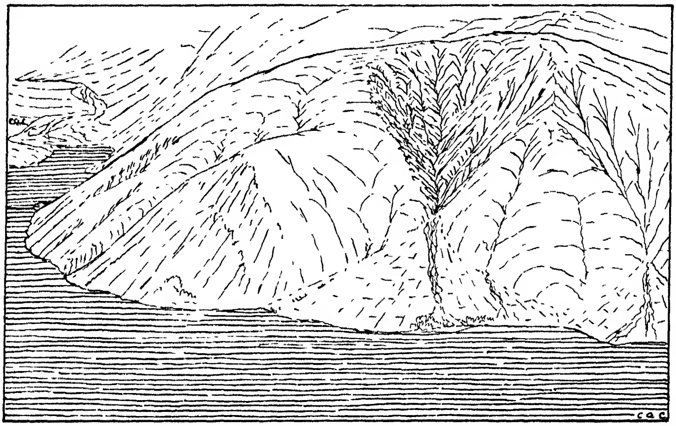

Fig. 89. Small non-glaciated hanging valley showing considerable modification by post-glacial erosion (note dimensions of fan at foot), in the moderately glaciated trough occupied by Lake Rotoiti, Nelson, New Zealand. (From a photograph.)

The Origin of Hanging Valleys

Any hypothesis favoured as an explanation of glaciated may be called upon to account for non-glaciated hanging valleys also, and vice versa. It is probably true that there is no single explanation for all the discordant junctions now found in glaciated regions; but there can be no doubt that many, probably most, of the typical hanging valleys of glaciated regions, whether themselves glaciated or non-glaciated, find their true explanation as the result of very considerable, in some cases profound, vertical corrasion that has taken place under the glacier tongues in trunk valleys. Such is the considered verdict of Richter, Gannett, Davis, Penck, and Gilbert,[10]

[9] W. M. Davis, *Die erklärende Beschreibung der Landformen,* pp. 439, 442, 1912; A Geographical Pilgrimage from Ireland to Italy, *Ann. Ass. Am. Geog.,* 2, p. 100, 1912.

[10] E. Richter, Geomorphologische Beobachtungen aus Norwegen, *Sitz. k.k. Akad. Wien, Math. Nat. Cl.,* 105 (1), pp. 147-189, 1896; H. Gannett, Lake Chelan, *Nat. Geog. Mag.,* 9, pp. 417-428, 1898; W. M. Davis, Glacial Erosion in France, Switzerland, and Norway (1900) *Geographical Essays,* pp. 635-689; A. Penck, Die Uebertiefung der Alpentäler, *Verh. VII Internat. Geog.-Kong. Berlin,* pp. 232-240, 1900; G. K. Gilbert, Glaciers, *Harriman Alaska Exped.,* 3, pp. 114-118, 1903.

and the evidence they relied upon has been confirmed by many later observers. Any attempt to find a general explanation that will supplant the theory of vertical glacial corrasion savours of special pleading.

The simple theory that vertical corrasion has lowered the floors of glacial troughs so rapidly that their deepening has outpaced that of tributaries may explain glaciated and non-glaciated hanging valleys alike, just as the simple theory of rapid vertical corrasion, in this case due to rejuvenation, accounts for discordant junctions in normal valleys. Gannett, Davis, Penck, and Gilbert, however, all conceived the idea of accordant junctions of the surfaces of secondary with trunk glaciers on the sites of hanging valleys, the present discordance of the floors of which is attributed to the vastly greater thickness of the main glacier as compared with that of its tributary. In Fig. 90 (centre) a glacier-filled valley system is shown, in which the glaciers make accordant junctions, and (at the right) a similar valley system from which the glaciers have melted away so as to expose hanging side valleys.[11] Thus many glaciated hanging valleys may be regarded as homologues not of young discordant but rather of mature accordant junctions of river-cut valleys, for in the latter a small step-up of the floor of the river channel may be expected to occur also as one passes from a main stream into a tributary. It cannot be assumed, however, that all the glaciers formerly occupying glaciated hanging valleys joined the glaciers in the main troughs accordantly, though many must have done so at the height of an ice flood.

Gilbert, true to the principle of multiple working hypotheses, has suggested as alternatives to the foregoing: (*a*) a hypothesis of widening, accompanied by little or no deepening, of a preglacially rejuvenated and still young valley along which tributary junctions were already discordant; and (*b*) the unlikely, or at least exceptional, case in which slight, if any, modification of the form of the main valley was required, it having been already broadened out after rejuvenation to the full width of a belt of very weak rocks bordered by resistant formations competent to delay the valley-cutting activity

[11] A magnificent photograph of the Barnard Glacier, Alaska, by H. B. Washburn, Jr. (*Geog. Jour.*, 98, photo 5, opp. p. 216, 1941), shows perfectly accordant junctions of three relatively small secondaries, the ice of which, as is indicated by curving lines of surface moraines, coalesces with the main stream.

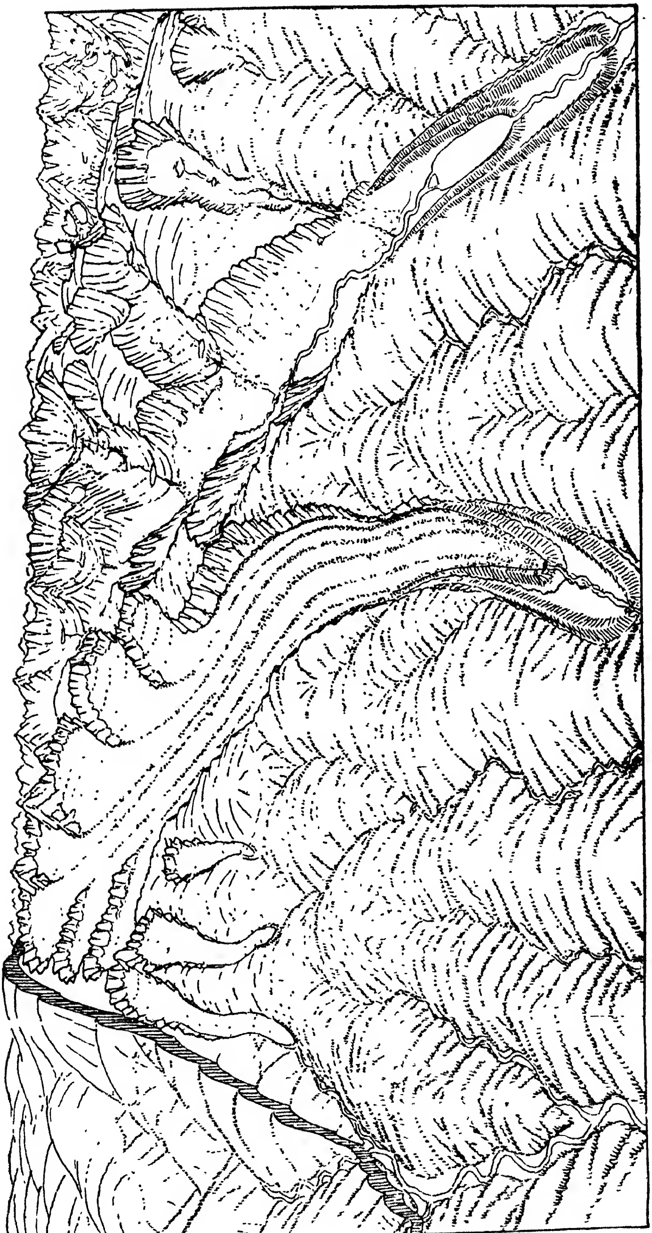

Fig. 90. A three-stage diagram, drawn by W. M. Davis, illustrating the glacial sculpture of mountains. "On the extreme left, a non-glaciated mountain mass . . . Across the middle, same kind of mountains after they have been well modified by the glaciers which still occupy their valleys. On the right, the same after the glaciers have disappeared, so that the cirques and troughs which they have excavated are exposed to view" (Davis).

of tributaries so that they were already in preglacial hanging valleys. The latter of these alternative hypotheses calls for no comment. As regards the former, this is the gist of the hypothesis advocated earlier by McGee[12] and of that advanced later by de Martonne,[13] who, however, does not exclude the probability of moderate deepening accompanying the development of the main trough by retreat of the side walls.[14] The theory of accordant glacier junctions is rejected by de Martonne, who regards the occurrence of a rock bar (perhaps holding up a lake—Pl. XXIII, 2) across the mouth of a hanging valley as typical, and explains its presence as the result of weakening of corrasion under the secondary glacier at a point where it descended as an ice-fall to join the trunk glacier, just as the shrunken Rhone Glacier now descends a steep slope on emergence from its hanging valley (Pl. XXXV, 2; and Fig. 91) and may have done so even when the valley below was occupied by a trunk glacier.

The fiords of Spitsbergen, which are trunk-glacier troughs recently in part vacated by shrinkage of glaciers still occupying their heads, are bordered by hanging valleys at frequent intervals, still containing glaciers (Pl. XXXIV, 1; and Fig. 92). The smaller of these valleys, containing hanging glaciers, hang high above tide-water level: the larger glaciers have their floors below sea-level. The heights of discordance seem to be so related to the sizes of the glaciers that, with the exception of a few corrie glaciers perched at great heights, all may quite possibly have joined the mains accordantly at the height of an ice flood, though it must be admitted there may be room for a difference of opinion on this point.

[12] W. J. McGee, Glacial Cañons, *Proc. Am. Assoc.*, p. 238, 1883; *Jour. Geol.*, 2 pp. 350-64, 1894.

[13] E. de Martonne, L'érosion glaciaire et la formation des vallées alpines, *Ann. de Géog.*, 19, pp. 289-317, 1910; 20, pp. 1-27, 1911; Quelques données nouvelles sur la jeunesse du relief préglaciaire dans les Alpes, *Rec. de Trav. Cvijic'*, pp. 121-140, Belgrade: 1924.

[14] W. M. Davis has rejected the hypothesis of de Martonne, at least in its general application, as an explanation of hanging valleys. The occurrence of two-storied hanging valleys, for one thing, is "essentially inconsistent with it," as it "demands strong erosive power on the part of the mid-height side glacier, independent of any gorge . . . in the floor of the main valley in immediately preglacial time. . . . The preparatory erosion of a normal gorge in the floor of a mature valley would facilitate the excavation of an overdeepened trough by glacial erosion; but even if so, it does not follow that this favourable condition was presented." (A Geographical Pilgrimage from Ireland to Italy, *Ann. Ass. Am. Geog.*, 2, pp. 97-98, 1912.)

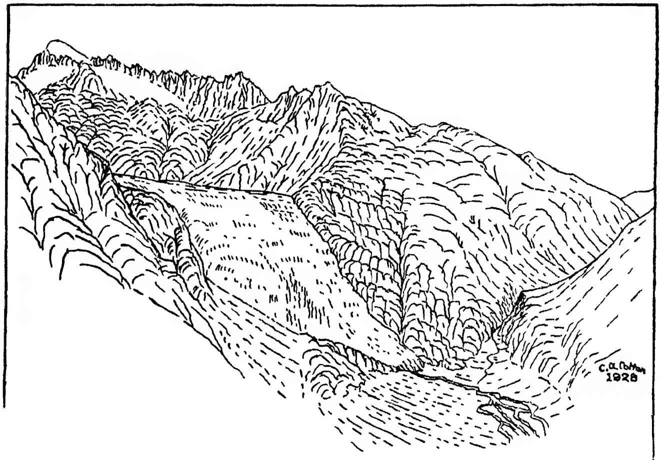

Fig. 91. The hanging valley still occupied by the Rhone Glacier, Switzerland.

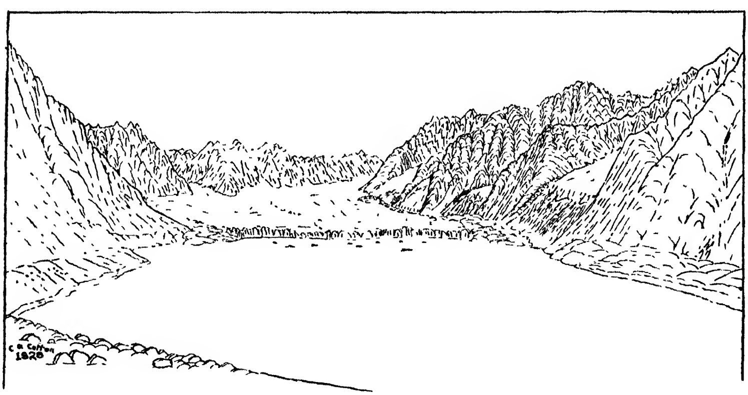

Fig. 92. Tide-water glacier at the head of an arm of Miller Fiord, Spitsbergen. Secondary glaciers occupy hanging valleys at the right, and one joins the main accordantly at the left.

Hanging Valleys Developed from Snow-line Corries

There is still another explanation available for hanging valleys and it is one which seems to be correct for the cases to which it has been applied. It explains many small, or at any rate short, hanging valleys perched high above the main floors as being simply cirques which have developed from high-set preglacial niches due to

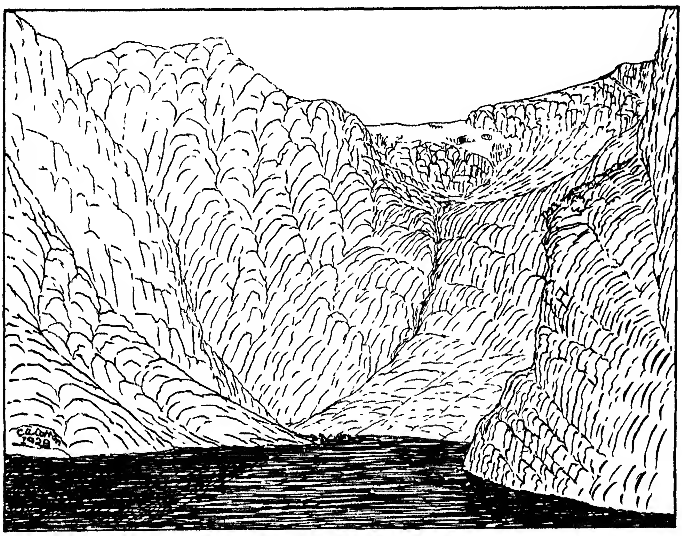

Fig. 93. Cirque hanging high on the wall of Nærofjord, Norway.

structure and weathering or from nivation hollows or possibly interglacial rasskars (p. 201) on upper slopes (Fig. 93). A great many of the features that figure as hanging valleys are no more than corries; but head-wall sapping has in some cases enlarged such forms to the dimensions of valleys. Speight[15] has thus explained hanging valleys bordering some of the Alpine valleys of Canterbury, New Zealand, which have been themselves only very moderately glaciated and in which the junctions of the larger tributaries (somewhat evened up by aggradation) are accordant. Examples have been described which are at fairly accordant heights

[15] R. Speight, Note on the Hanging Valleys of the Upper Rangitata Valley, *Trans. N.Z. Inst.*, 54, pp. 90-98, 1923.

above the main valley floors, so that they are evidently related to the snow-line of the Glacial Period. They are referable to various stages of development from scarcely altered niches, or nivation cirques, to valleys that seem to have grown to a considerable length by glacial headward erosion and have been scoured to a U-form by the glaciers they have nourished (Pl. XXXVI, 1). Hanging valleys of cirque origin are common in most glaciated mountains. It is on record, for example, that in some valleys of the European Alps hanging side valleys are present only on the sides facing north and east[16]—the aspects that favour development of corrie glaciers (p. 182).

Bastions

Projecting into the main valley in front of a true glacial hanging valley (if one may thus temporarily exclude from the category those hanging valleys developed from high-level cirques) there is sometimes to be found a "bastion"[17] of solid rock projecting at or below the level of the junction (Pl. XXXVI, 2; and Figs. 94, 95). Bastions, however, are by no means invariably present in apparently favourable situations. The presence of a bastion does not indicate whether the main valley has been excavated vertically or laterally, though it is consistent with any hypothesis of strong glacial erosion. It shows that the power of the main glacier to erode has been weakened, or erosion by it retarded, at the junction, apparently because its flow has been affected by the thrust exerted at right angles to it by the ice stream from the secondary. A bastion at the junction may be taken to indicate that the glaciers joined with some approach to accordance of surface levels.

Where bastions are partially destroyed by continued glacial erosion their abraded basal remnants become knob fields like those which mark the sites of imperfectly truncated spurs (Chapter XVIII).

[16] E. J. Garwood, Features of Alpine Scenery due to Glacial Protection, *Geog. Jour.*, 36, p. 317, 1910.

[17] Such features, though many observers are familiar with their appearance in the field, have rarely received special mention in written descriptions and have only recently been named. O. Flückiger (Glaziale Felsformen, *Pet. Mitt. Ergänzungsheft*, 218, 1934) has termed the form *Felsvorbau* or *Felsbastion*, but the latter term is used in a different sense by Richter (Geomorphologische Untersuchungen in den Hochalpen, *Pet. Mitt. Ergänzungsheft*, 132, p. 51, 1900). As the English equivalent of *Felsvorbau* the term "bastion" has been used by O. D. von Engeln (Rock Sculpture by Glaciers: a Review, *Geog. Rev.*, 27, pp. 478-482, 1937).

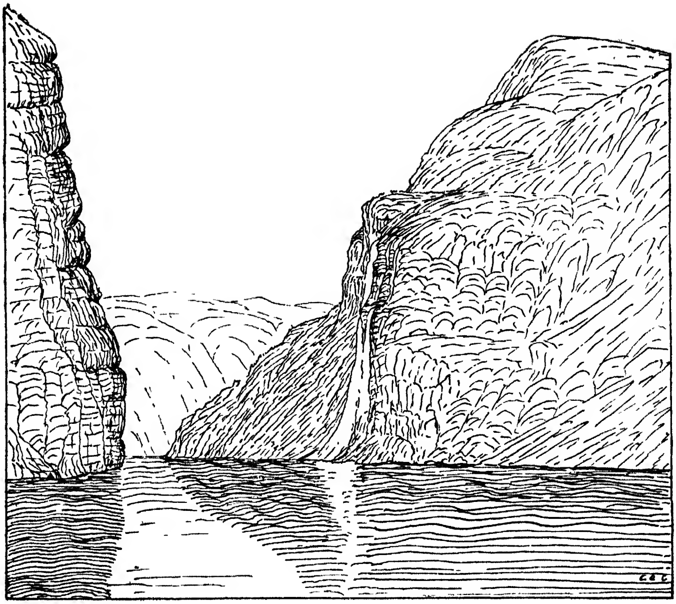

Fig. 94. The Seven Sisters waterfalls cascade over a bastion into Geiranger Fiord, Norway.

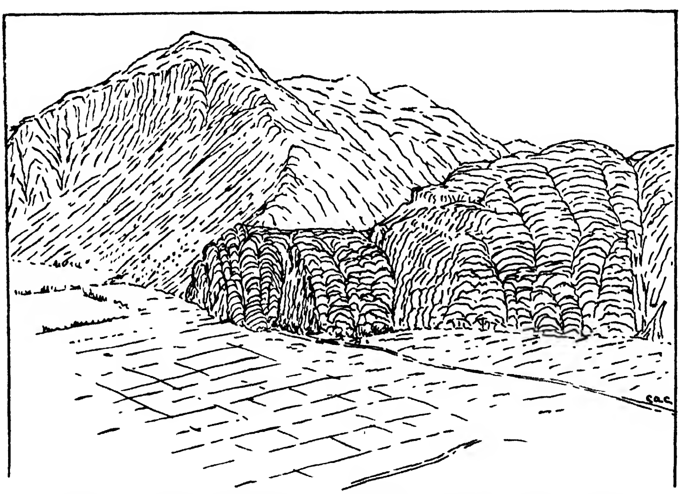

Fig. 95. Bastion at the junction of the Trient hanging valley with the trough valley of the Rhone. (Drawn from a photograph.)

Mock Hanging Valleys of Glacial Diffluence

"Mock" hanging valleys are generally present where distributary ice streams have left the main valley (Pl. XXXVII, 1). "Glacial-diffluence" passes[18] (Fig. 96) are often of this nature. In some cases a dimple is present in the wall of the main trough at the point of diffluence—the reverse of a bastion.[19]

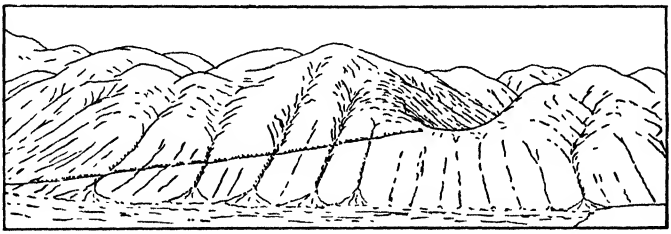

Fig. 96. Trough-side notch resulting from glacial diffluence and having the appearance of a hanging valley, route of St. Gotthard railway, at the head of Lake Maggiore. (After Davis, redrawn.)

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[18] J. Sölch, *Studien über Gebirgspasse,* p. 243, Stuttgart, 1905.
[19] O. D. von Engeln, *loc. cit.* (17), p. 482.

CHAPTER XVIII

Spur Truncation; Ice-Shorn Hills; Mammillated Landscapes; Glacial Terraces

THE CONVERSION of river valleys into glacial troughs involves generally the elimination from them of some of their curves and windings, for the perfected glacier channel has curves only of wide radius (Pl. XXXVII, 2). The preglacial forms of glaciated valleys cannot be regarded as conforming to any one type: they must be many and varied. Some must have zigzagged sharply between overlapping spurs, while others have been comparatively straight; and of the latter some may have still been narrow and V-shaped, while others had developed a broader U form. Even valleys in this last category, however, may turn too sharply to suit the mechanics of flow of a glacier stream, and they may require modification at points where they swing a little too far to right or left, even if the channel provided by the preglacial valley is such as to accommodate the glacier elsewhere with little change of form, though perhaps requiring some enlargement. Those less fully mature river valleys which have assumed zigzag curvature during their youthful period of vertical incision but are still narrow-floored enough to wind about among the overlapping valley-side spurs thus developed are converted into glacial valleys of trough form only by the ruthless truncation of these overlapping spurs. This is equally the case whether the process of straightening is or is not accompanied by deepening of the valley.

The extent to which glaciers have succeeded in straightening the valleys they occupy varies very widely; some still closely follow some preglacial valley windings. On the Alaskan coast near Juneau, for example, where glaciers still descend to sea-level, and where some of their valleys have been converted into typical troughs bordered by lines of spur-end facets (as in the valleys of Eagle and Herbert Glaciers), others show little modification of the inter-

locking valley-side spurs of the preglacial valleys. Thus notable tapering spurs with little-altered preglacial slip-off slopes faced by undercut amphitheatres still survive in the valleys of Norris and Taku Glaciers.[1] There is a contrast in this respect, indeed, between the two closely adjacent valleys of the nearby Twin Glaciers (Fig. 97). In the eastern Twin truncation of spurs has been far advanced prior to the shrinkage of the glacier that has followed the ice flood

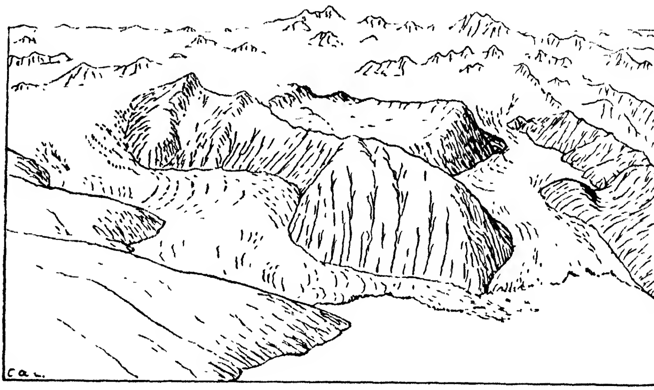

Fig. 97. Twin Glaciers, Alaska. View looking north. (From a photograph.)

of the last glacial epoch; but in the valley of the western Twin slip-off slopes still remain on spurs projecting into amphitheatres. These must survive from a preglacial landscape, for otherwise glacier ice must here be credited with the development of progressively increasing curvature in its valley, and with greater flexibility of flow and greater ability to corrade laterally by actually undercutting the valley wall than it usually appears to possess.

Faceted Trough Walls

Spur-truncation, if accomplished by lateral glacial corrasion, develops a "faceted" type of trough-side (Figs. 98, 99). In some valleys, however, lateral corrasion by a preglacial river may have already trimmed off interlocking spurs, and only the final touches on the facets may be glacial work. Another agency which some

[1] For illustrations see Wentworth and Ray, Studies of Certain Alaskan Glaciers in 1931, *Bull. Geol. Soc. Am.*, 47, pp. 879-934, Pls. 1, 3, 4, 1936.

opponents of all theories of very extensive glacial erosion have appealed to in explanation of the lateral expansion of troughs is intense frost action.[2] Thus by some means or another spurs may have been in some cases partly demolished before being eventually overrun by ice, faceted, and either completely truncated or reduced

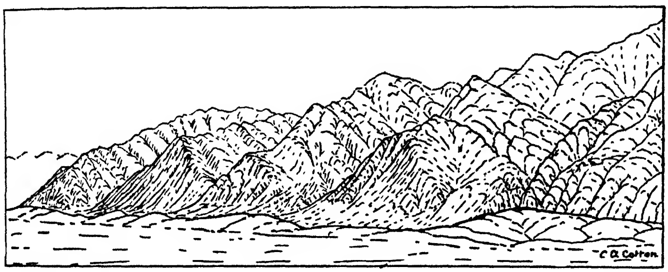

Fig. 98. Faceted trough wall resulting from spur-truncation, west side of the Hawea valley, New Zealand.

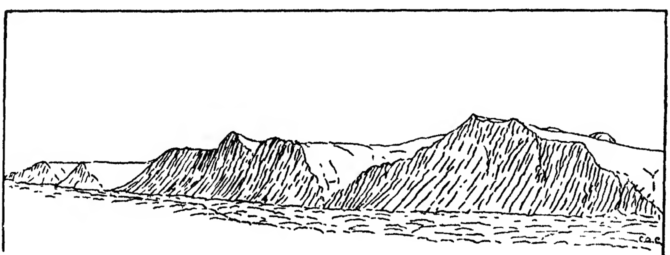

Fig. 99. High trough-wall facets at Mt. Allan Thomson, seen at a distance of 10 miles across the Mackay outlet glacier, Antarctica. (Drawn from a photograph.)

to fields of worn knobs (Fig. 100). Absence of conspicuously hanging side valleys, which has been noted for example as a peculiarity of obviously glaciated troughs in the Canterbury district of New Zealand,[3] though resulting in this case partly from post-

[2] Theory of J. Sölch (see pp. 213-4); compare Taylor's hypothesis of trough-wall development by frost sapping (pp. 212-3); also F. Nansen, Strandflat and Isostasy, *Vidensk. Skr., M.-N. Kl. 1921,* 11, p. 22, 1922.

[3] R. Speight, Note on the Hanging Valleys of the Upper Rangitata Valley, *Trans. N.Z. Inst.,* 54, see p. 93, 1923.

glacial aggradation of the valley floors, is an accompaniment also of lateral (rather than vertical) enlargement of valleys, whether entirely or only in part by glacial erosion, such as produces typically faceted side walls.[4] In valleys so enlarged some basal remnants of truncated spurs in the form of knob fields are commonly found

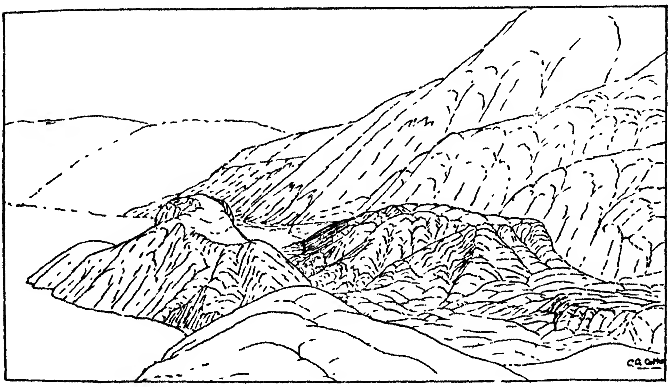

Fig. 100. Faceted north wall of the Rangitata valley, New Zealand, showing a basal remnant of a truncated spur in the knob field known as the Jumped-up Downs.

unless the rock floor of the valley is hidden by morainic or alluvial accumulations. The important part played by lateral glacial erosion in truncating valley-side spurs was recognised by Harker in the Cuillin Hills of Skye;[5] and examples of the progressive conversion of a winding valley into a trough by spur truncation in the Hardanger district of Norway are described by Ahlmann.[6]

In valleys, on the other hand, that have been greatly over-deepened, the valley floor has been excavated far below that of the preglacial valley, so that any facets resulting from truncation of spurs that may have interlocked in a winding preglacial valley are now perched high on the side slopes of a wall-sided trough, and obviously no remnants of such spurs can survive on the floor.

[4] R. Speight, The Modification of Spur-ends by Glaciation, *Trans. N.Z. Inst.*, 53, pp. 47-53, 1921.

[5] A. Harker, Ice Erosion in the Cuillin Hills, Skye, *Trans. Roy. Soc. Edinburgh*, 40, pp. 221-52, 1901.

[6] H. W. Ahlmann, Geomorphological Studies in Norway, *Geografiska Annaler*, 1, p. 73, 1919.

Even in overdeepened valleys, however, spurs separating confluent branches have commonly been overridden by ice at the points of confluence and so truncated; and landscape evidence of this is generally available if the truncation has been incomplete.

Basal Remnants of Spurs

The remnants of spurs in a penultimate stage of destruction are fields of separate glaciated knobs, classic examples of which are those in the valley of the Rhue (central France) and in the Sawatch Range (Colorado) figured and described by Davis,[7] who called them "unfinished pieces of work, which would have been more

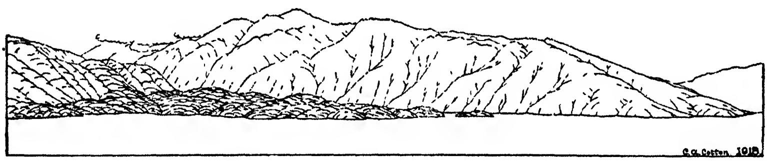

Fig. 101. Spur overridden, truncated, and ice-shorn at the confluence of the South Fiord trough with the main glacial channel of Lake Te Anau, New Zealand.

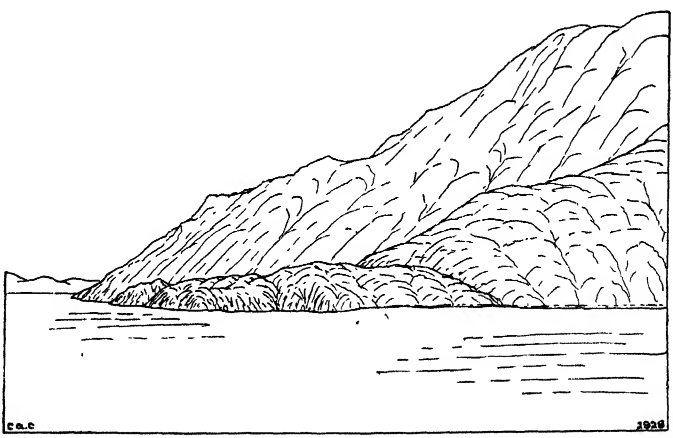

Fig. 102. Basal remnant of a truncated spur, opposite Stybarrow Crag, Ullswater, England.

[7] W. M. Davis, Glacial Erosion in France, Switzerland, and Norway (1900), *Geographical Essays*, pp. 636-8; Glaciation of the Sawatch Range, Colorado, *Bull. Mus. Comp. Zool. Harvard*, 49, pp. 1-11, 1905.

completely scoured away had the glacial action lasted longer." Many examples of such knob fields are known (see Pl. XXXVIII, 1 and 2; and Figs 101, 102).

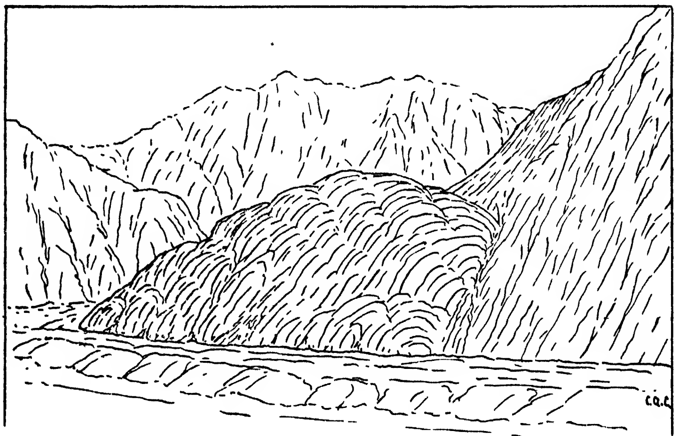

Fig. 103. Domed form of semi-detached remnant of a truncated spur, Jim's Knob, Rakaia glacial trough, New Zealand. (From a photograph by R. Speight.)

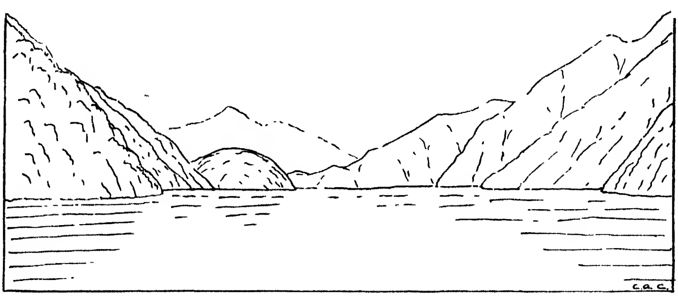

Fig. 104. Beehive form of basal remnant of a partially truncated spur, Thompson Sound, Fiordland, New Zealand. (From a photograph by R. Speight.)

Instead of typical knob fields, however, many single broadly-rounded ice-shorn domes or hills of simple outline mark the survival of basal parts of spurs of large dimensions at points of glacial

confluence; and a smoothly-domed "beehive" form is rather commonly developed at an early stage of transection prior to the eventual reduction of a spur to a knob field[8] (Pl. XXXIX, 1 and 2; and Figs. 103, 104).

Beehive Forms

The "semi-detached" knobs, sugarloaves, or beehive forms nestling at the base of a trough wall, as they have been observed by Andrews and Speight in the New Zealand fiords, somewhat suggest the forms of kernbuts (residual buttresses in front of fault scarps) or — if low enough — partly worn-down bastions (p. 232). The Norwegian example shown in Pl. XXXIX, 2 is of grander proportions (see also Fig. 77A).

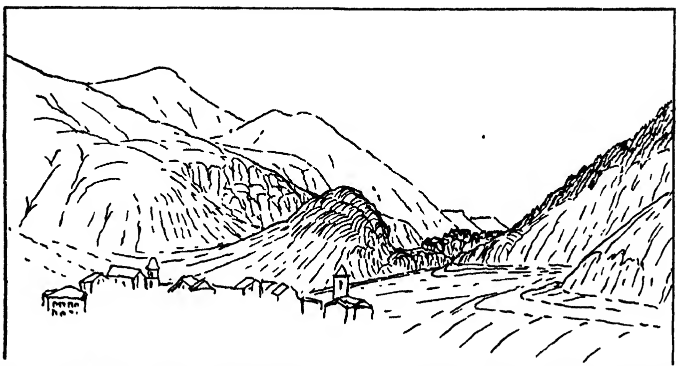

Fig. 105. Riegel at Bivio, Oberhalbstein valley, Eastern Alps. (After a photograph by Solch.)

One can only speculate as to the mechanism of the process of glacial erosion which separates spur-ends as domes before wearing them down farther. Though these beehive forms are features of one side only of broad valleys, their shaping has something in common with the development of rounded residual ice-shorn hills[9] (Fig. 105) on the transverse rock bars termed "riegels" (Chapter XIX), especially where such a rock bar is transected by a pair of scoured-out gaps such as are sometimes regarded as characterising the typical riegel form.

Various attempts have been made to explain such twin gaps. One speculation, for example, which, however, is not thought to

[8] R. Speight, *loc. cit.* (4).
[9] Termed "inselbergs" by J. Sölch (*Pet. Mitt. Ergänz.*, 220, p. 175, 1935).

afford an explanation of general application, is that of Brunhes,[10] who regarded them as representing the erosive work of a pair of subglacial torrents, one at each side of a glacier. Nussbaum,[10a] who, like de Martonne, ascribes the vertical incision of most channels that have been occupied and modified by ice to preglacial and interglacial river work, has suggested a hypothesis for the origin of a pair of gaps through a riegel (Fig. 106) which assumes that

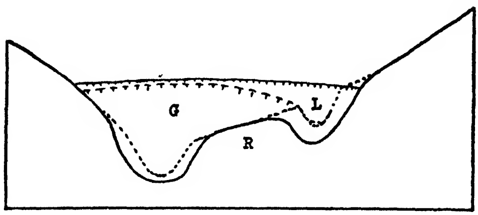

Fig. 106. Riegel developed as a result of partial truncation of a spur. R, riegel; G, glacier—two stages; L, lateral stream-cut gorge, later occupied, deepened, and enlarged by the glacier. (After diagrams by Nussbaum.)

a gorge is incised through the neck of an overridden spur by a lateral stream of glacial melt-water, this being enlarged by ice scour when the glacier subsequently extends over it. Incision of gorges in bedrock by lateral melt-water streams has been observed in progress near the terminal faces of glaciers in Alaska[11] (Pl. LVIII, 2).

Ice-shorn Hills

A special case of incomplete destruction of spurs is found where ice from convergent valley glaciers has united in an intermont basin as a thick "piedmont" glacier that still has movement and can erode. Where such a glacier deploys across ridges or long spurs these may be shorn down to rows of knobs, which are most conspicuous if they rise as islands above the surface of a post-glacial lake, as is the case in a New Zealand example, the beautiful island-dotted Lake Manapouri. Here

[10] J. Brunhes, Érosion fluviale et érosion glaciaire, *Rev. de Géog. ann.*, 1, pp. 281-308, 1906-7.

[10a] F. Nussbaum, Beobachtungen über Gletschererosion . . . , *C-R. XV Cong. internat. Géog.*, 2, pp. 63-73, 1938.

[11] O. D. von Engeln, Phenomena Associated with Glacier Drainage and Wastage, *Zeits. f. Gletscherk.*, 6, pp. 104-150, 1911.

> the chief complex of spurs entering the basin occupied by the lake reaches down from the north . . . , whereas the direction of the chief ice stream was from the west, and in its passage eastward it cut across the long trailing ridges of the preglacial land surface. Erosion was most marked in the western reaches of the lake, where the ice was thickest. . . . The change in the eastern spurs has been slight, merely cutting . . . a series of notches . . . all with the same characteristic profile and continued down to lake level, where exactly the same landscape form is reproduced in the islands that dot the lake. . . . Still farther eastward the spurs are unmodified.[12]

Other ice-shorn hills now isolated as a result of glacial erosion but formerly parts of continuous ridges owe their isolation to erosion following glacial overflow and diffluence. One type of shorn knob common in the Canterbury foothills of the New Zealand Alps has originated as follows, according to Speight.[13]

The preglacial drainage pattern has been obliterated as a result of glacial diffluence, and the isolated hills are explained as remnants

Fig. 107. An intercatenary ridge drowned to form a peninsula between the two arms of Moke Lake, Lake Wakatipu district, New Zealand.

of formerly continuous dividing ridges between minor stream valleys that have been occupied by ice. These have been narrowed and partly demolished by the lateral abrasion of parallel ice tongues. Such forms project above the confluent ice as nunataks; but some of these may be overridden by a later ice flood.

[12] R. Speight, *loc. cit.* (4), p. 49.

[13] R. Speight, Morainic Deposits of the Waimakariri Valley, *Trans. Roy. Soc. N.Z.*, 68, pp. 143-160, 1938.

Whether they have been reduced to isolated hills or remain to form continuous divides between postglacial rivers, residual ridges between adjacent catenary troughs exhibit a characteristic isosceles-triangular transverse profile produced by intersection of the side walls of parallel troughs (Fig. 107).

Roches Moutonnées and Crag-and-tail Forms

The landscape forms which for many years have been given by English writers their old Alpine name "roches moutonnées"[14] occur grouped as knob fields in the basal remnants of prominent salient forms such as spurs that have been truncated by glacial erosion, and also more widely as grouped or isolated features rising above most rock floors developed by glacial corrasion whether under ice sheets or valley glaciers. It is the appearance of isolated roches moutonnées (Pls. XL, 1, 2; XLI, 1) that has earned for them this quaint appellation. Where shaped from light-coloured rock, scraped bare and mammillated, and viewed from afar through the clear atmosphere of their mountain environment in which one loses the sense of perspective, they simulate sheep though in reality immensely larger. Small-scale mammillation of the surface of the knob, if present, may suggest a resemblance to the fleece.

In form these knobs vary considerably, depending on the alignment of rock structures in them,[15] but a rather characteristic shape is elliptical, elongated in the direction of ice flow and smoothly streamlined, at least on the sides and upstream end. The downstream end may be more irregular in form. Signs of abrasion (scour) may be visible on all parts of the knob but are most conspicuously present on the upstream (or "stoss") side, which has come to be termed for this reason also the "scour side",[16] while the less regular downstream (or "lee") side may show re-entering angles owing to the fact that partial destruction of the knob beneath the ice has been effected by the plucking process (p. 146). Thus the lee side is termed also the "pluck" side. In the case, on the other hand, of some knobs that are equally worn and rounded

[14] The German equivalent is *Rundhöcker*. In some cases we may substitute "glaciated knobs" for the exotic term, as has been done by W. M. Davis.

[15] O. Flückiger, Glaziale Felsformen, *Pet. Mitt. Ergänzungsheft*, 218, pp. 7-11, 1934.

[16] So called by A. Penck (*Rep. VIII Internat. Geog. Congr.*, p. 177, 1905) following a suggestion by Shaler.

on the scour side by glacial abrasion (especially where this has been effected by an ice sheet of no great thickness) the lee side of a knob is less steep and presents a "tail" of streamlined form; but this is found to consist of deposited glacial debris which has collected in the lee of the knob, thus developing the "crag-and-tail" form of knob characteristic of some glaciated regions.[17]

The tendency is thus for both abraded and deposited features developed beneath ice to combine to "present gently flowing outlines which are convex upward".[18] "Unquestionably the most notable feature of a well-glaciated country is its rounded and flowing configuration. . . . This is the direct result of glacial abrasion, but accumulation also has helped in the production of a flowing contour."[19]

The presence of a plucked lee side or, alternatively, of a tail of debris in the lee of a glaciated knob may depend in some way on the relation of the load of morainic debris the ice is carrying to its erosive capacity or may be related to lines of flow in the ice.[20] Unless it is a preglacial prominence little altered by glacial erosion the bedrock surface of the lee side of a glaciated knob may be expected to be steeper than the scour or stoss side; but a tail, if present, masks this form. Crag-and-tail features are in some cases of large dimensions, the Castle Rock in Edinburgh being an example often cited.[21] In such cases, however, the foundation of the feature is a preglacial hill shorn and scoured but perhaps not very much reduced in dimensions. Shorn hills may be without tails, in which case they generally present somewhat steep lee sides, perhaps plucked. Such a shorn hill, which was overridden by the ice of the Godley Glacier (New Zealand) during the ice flood of the Glacial Period is shown in Pl. XLI, 2.

Glacial Scour

The effects of glacial scour are visible on overridden surfaces of hard rock, which may exhibit an almost perfect polish (Pl. XLII, 1),

[17] J. Geikie, *Earth Sculpture,* p. 194, 1898; Wooldridge and Morgan, *The Physical Basis of Geography,* p. 390, 1937.

[18] W. H. Hobbs, *Earth Features and their Meaning,* p. 318, 1912.

[19] J. Geikie, *loc. cit.* (17), p. 193.

[20] See reference to Chamberlin's "drumloidal curve" in Chapter XXIII.

[21] See, for example, W. B. Wright, *The Quaternary Ice Age,* 2ed., p. 62, 1937; also Wooldridge and Morgan, *loc. cit.* (17).

though flutings both broad and narrow are generally present and detailed examination reveals innumerable scorings and scratchings inflicted on the rock surface by the hard corners of the last sand and rock fragments dragged over it by the glacier (Pl. XL, 1). A detailed study by Chamberlin of the grooving, striation, and polish of rock surfaces scoured by the North American continental ice sheets of the Glacial Period has revealed many minor features, such as "chatter marks" and "jumping gouges" which throw much light on the nature of the movement of debris-laden bottom ice. Curved and irregular scratches made by stranded icebergs in lakes are readily differentiated from the more usual straight and parallel striae made by glacier ice[22] (Pl. LI, 1). Fragments of the ground moraine of the glacier which are thus dragged along in contact with the bedrock floor are themselves polished and striated in a similar way (Chapter XXIII).

On scoured surfaces of bedrock an older and a newer system of scratches may sometimes be found, indicating that a change in the direction of local ice movement has taken place. Possibly, however, one of two such systems may be a relic of an earlier glaciation, being perhaps present in such a case only in hollows of the rock surface from which a protective layer of debris has escaped removal by later ice scour.[23]

Boulders and fragments of all sizes of morainic debris may remain stranded on the scoured bedrock surface when a glacier melts (Pl. XLII, 1). It is indeed only under a protective layer of such material, and especially where this is of a clayey texture, that a scoured bedrock surface can long be preserved. If exposed to the atmosphere it is necessarily subject, like every bare-rock surface, to mechanical and chemical disintegration. Except where they have been protected by a cover, glacially scoured surfaces showing polish and minor scratchings survive only if they have been very recently exposed by withdrawal of ice from them near terminal faces of present-day glaciers, shrinkage of which reveals scored and polished trough floors and walls. Larger forms shaped

[22] T. C. Chamberlin, The Rock Scorings of the great Ice Invasions, *U.S. Geol. Surv. Ann. Rep.*, 7, pp. 147-248 (profusely illustrated), 1888.

[23] T. C. Chamberlin, *loc. cit.* (22), p. 176; W. H. Hobbs, *Earth Features and their Meaning*, p. 304, 1912.

by glacial scour and plucking have survived more abundantly since the Glacial Period, however, having commonly escaped postglacial dissection, though weathered at the surface.

Mammillated Surfaces

Glacial erosion, as described in earlier chapters, seems never to have developed extensive plains; and on a small scale, as Chamberlin has noted, the process of ice abrasion, without taking into account concomitant effects due to plucking, is not entirely "planative". "A glacier stream, like other streams, has its own differential habits of action, and under a general disposition to subdue the surface to a plane aspect there was a subordinate tendency to develop inequalities suited to facilitate its own flowage."[24]

The occasional nearly-level areas of small extent smoothed by abrasion, the convexities of roches moutonnées and of steeper and

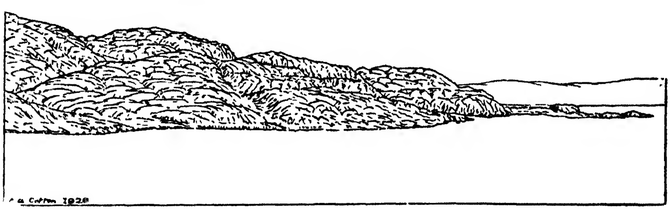

Fig. 108. Typical mammillated surface developed under an ice sheet, Kyles of Bute, Scotland.

larger glaciated knobs, and in addition innumerable ice-smoothed minor convexities of the extensive ice-shorn surfaces (Pls: XLI, 1; XLIII, 1, 2) termed "mammillated" by J. Geikie and other British glaciologists of the eighteen seventies, though they afford evidence of some local glacial smoothing, are at the same time all parts of surfaces left decidedly irregular by glacial erosion (Fig. 108). The surfaces of the strandflats of Norway and Alaska, though they probably have not been deeply abraded by glacial corrasion, have had all their details shaped under ice and afford some of the best available examples of ice-eroded surfaces that are broadly level and yet diversified. In Alaska a strandflat surface, as described

[24] T. C. Chamberlin, *loc. cit.* (22), p. 242.

by Gilbert,[25] "is somewhat uneven, low moutonnée bosses alternating with hollows that hold pools or bogs." Similar mammillated surfaces on the Norwegian strandflat are shown in many photographs by Nansen.[26]

Selective Glacial Erosion

Mammillated detail has been developed in every case over the surfaces of the larger features cut or isolated by glacial erosion in massive rocks, such as the domed or further disintegrated remnants of truncated spurs and bastions, the ice-scoured benches above trough-side shoulders (Pl. XLIII), and even the nearly-vertical sides of fiords, steepened obviously by lateral undercutting as well as by vertical corrasion (Pl. XLVII, 1). Similar moulding even of the unconsolidated materials of landslides and moraines has been observed, where these have been overridden by ice. The pattern of bosses on an extensive mammillated surface generally exhibits a considerable degree of regularity, and an investigation of such patterns may be expected to throw light on the reason for the differential character of glacial erosion, which causes it to produce a mammillated instead of a smooth surface.

It may not always be safely assumed that the bosses of the mammillated surface stand up in relief because they offer greater resistance to erosion than the intervening areas. In the case of a landscape from which little more than the preglacial waste mantle has been removed by the action of ice selective glacial erosion may have taken place as a result of irregular depth of preglacial weathering. The hypothesis that unweathered bosses have been merely stripped has a very limited application, however, for mammillated surfaces are as characteristic of very deep as they are of very shallow glacial corrasion, the knobs at the base of a great spur which has been shorn down a thousand feet being, as it were, first-order waves produced by glacial erosion on the bedrock surface, while their scoured sides exhibit secondary waves or mammillations. It seems quite probable that minor mammillations can result from the searching nature of selective glacial erosion acting even on

[25] G. K. Gilbert, Glaciers and Glaciation, *Harriman Alaska Expedition*, 3, p. 131. 1904.

[26] F. Nansen, Strandflat and Isostasy, *Vidensk. Skr., M.-N. Kl. 1921*, 11, 1922.

unweathered rocks. The processes of scour and pluck may have picked out parts of soft bands in gneissic and stratified rocks and excavated such belts and patches in massive rocks as are weakened by the presence of crowded joint fissures. Local "monolithic" absence of closely spaced joints is the explanation favoured by Matthes[27] for the survival of roches moutonnées in the granite terrain of California; but smaller bosses which are commonly present in a more or less regular pattern are not so easily accounted for.

Even on gneissic rocks Flückiger[28] has found the effects of selective glacial erosion to be well marked only at places where the strike of the gneissic banding happens to be parallel to the direction of ice flow. Elsewhere gneissic structure, he considers, controls only minor features of the erosion pattern, while the main undulations of any mammillated surface originate, on the other hand, in "a wave-like motion of the ice, which impresses itself on the subjacent rocks" (von Engeln). This idea of Flückiger's involves acceptance of a mechanical conception of "stationary" waves in an ice stream, the theory of which presents insuperable difficulties,[29] however, and such a hypothesis in explanation of the mammillated surface pattern of an ice-scoured landscape may be considered only with the greatest reserve.

As regards some isolated rock knobs the hypothesis that they are surviving preglacial prominences merely shorn by the ice must receive consideration. As Penck[30] has pointed out, however, there is no justification for offering such survival as a general explanation of the existence of roches moutonnées (as has very often been done).[31] Some relatively large features sometimes thus classed, but better placed in the category of ice-shorn hills, are obviously derived from preglacial forms in lightly-glaciated regions—for example, the larger crag-and-tail forms of Scotland (p. 245). True roches moutonnées, however, retain no traces of preglacial forms,

[27] F. E. Matthes, Geologic History of the Yosemite Valley, *U.S. Geol. Surv. Prof. Paper*, 160, pp. 95-6, 1930.

[28] O. Flückiger, *loc. cit.* (15), p. 9.

[29] M. Demorest, Glacial Movement and Erosion: a Criticism, *Am. Jour. Sci.*, 237, pp. 594-605, 1939.

[30] A. Penck, *loc. cit.* (16).

[31] W. B. Wright, for example, has explained roches moutonnées in general as the result of "the passage of ice over prominent knobs of rock" (*The Quaternary Ice Age*, second edition, p. 42, 1937).

but are developed, like mammillated surfaces of relatively small relief, entirely by glacial erosion.[32]

Some landforms too large to be classed as roches moutonnées —rather of the dimensions of ice-shorn hills—which are known in West Greenland have been developed entirely by glacial erosion under the continental glacier but have dip-slopes and escarpments controlled by a gneissic banding in the terrain, the influence of which has been strong enough locally to preclude development of the gentler scour sides and steeper pluck sides characteristic of at least the smaller ice-shaped rock forms in most terrains.[33]

The forms of true roches moutonnées and glacial mammillated relief being entirely the products of glacial erosion, it cannot be assumed that they will all be smoothed away by a continuance of the same process. Davis assumed (and perhaps his deductions based on this assumption are unjustifiable) that continued glacial abrasion of the floors of troughs would reduce them to smaller detailed relief. While this is undoubtedly the case as long as spur ends and other preglacial irregularities remain to be smoothed away, the generalisation regarding progressive reduction of mammillated relief is premature.[34] Under a powerful ice stream lower relief of the mammillated surface is developed, according to Flückiger,[35] in the middle of the trough, where the current is strongest, greater convexity of bosses being present towards the sides, but such differences in the measure of the relief do not seem to be characteristic of particular stages of erosion.

Glacial Terraces

Glacially terraced slopes—such as are well known in southern New Zealand—afford a distinct variant of the roche-moutonnéed and mammillated type of ice-worn surface. Such terracing is developed most perfectly on schist terrains. At some localities in

[32] It is clear from W. M. Davis's descriptions of truncated spurs (pp. 239-40) that he regarded many roches moutonnées, and especially those grouped in knob fields, as remnants of salient preglacial forms. Contrary to Flückiger's interpretation of his point of view, however, it is equally clear that he ascribed all the details of such forms to glacial erosion.

[33] M. Demorest, *loc. cit.* (29), p. 605.

[34] This generalisation is implied in Figs. 145 and 146 of W. M. Davis's *Die erklärende Beschreibung der Landformen*, 1912.

[35] O. Flückiger, *loc. cit.* (15), pp. 9, 16.

the North-west Otago district of New Zealand glacial terraces form numerous valley-side steps which are remarkably regular and horizontal for short distances. Elsewhere, however, they are irregularly inclined in haphazard directions, so that there is nowhere danger of their confusion with flights of river-cut terraces. Those at Lake Luna (Pl. XLIV, 1) have been described as follows: "These ice-cut terraces . . . vary from 30 feet to nearly 70 feet in height and from a few yards to over two chains in width. They are excavated in a fairly hard quartzose mica-schist. The broader benches often have an undrained depression at the back, generally close under the slope ascending to the next platform."[86]

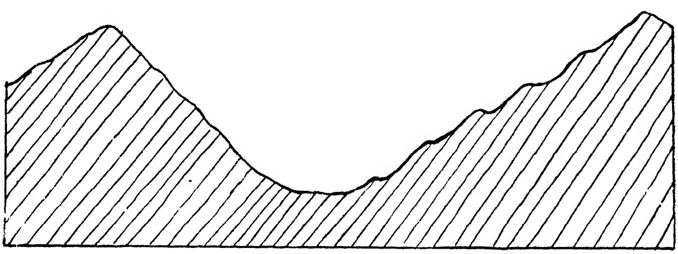

Fig. 109. Structurally controlled glacial terraces and homoclinal glacial trough in schist terrain.

Another observer has more recently emphasised the characteristics of the terraces by referring to the individual features as "grooves" and "benches".[87] This observer explains the terraces as a result of structural control of glacial sculpture. The schist foliation and a parallel structure of alternating bands of harder and softer schist are inclined at a considerable angle, and conspicuous terraces make their appearance only on this terrain and on dip slopes, or, strictly speaking, on slopes less steep than the dip and truncating it very obliquely (Fig. 109).

Some of the troughs in which these terraces occur are homoclinal strike valleys with a rather marked asymmetry of transverse profile. This might be regarded as a survival of a preglacial valley form but for the very considerable depth of glacial erosion, and the

[86] J. Park, The Geology of the Queenstown Division, *N.Z. Geol. Surv. Bull.*, 7, p. 19, 1909.

[87] R. W. Willett, unpublished dissertation.

profile appears actually to result from a structural control of the trough form as it is developed by glacial corrasion. Such control may be inoperative, however, under glaciers much thicker than those which excavated these homoclinal valleys (about 1000 feet thick, as estimated by Willett), for larger troughs on a similar terrain in the same district, which were excavated under glaciers several thousand feet thick, have been opened out to a symmetrical catenary or trough form of transverse profile regardless of the structure (Lake Wakatipu trough, for example, Pl. XLVI, 2). Structurally controlled terraces are present on the sides of major troughs as well as minor valleys, however (Pl. XLIV, 2). Thus, though the replacement of the homoclinal profile by the U form of trough may result from indifference to structure induced by the "grossness of the attacking process", to use von Engeln's[38] expression, glacial erosion seems still capable here of searching out the minor differences of rock hardness which give rise to groove-and-bench glacial terraces.

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[38] O. D. von Engeln, Glacier Geomorphology and Glacier Motion, *Am. Jour. Sci.,* 35, p. 426, 1938

CHAPTER XIX

Trough-Floor Steps; Riegels and Basins

GLACIAL-TROUGH floors are notoriously uneven in longitudinal profile. Not only are there many steep descents in them irregularly spaced, but another feature also commonly found is reversal of slope on the rock floor. Thus are formed the rock-rimmed basins that contain many of the postglacial lakes in upper valleys of Alpine regions, though other similarly situated lakes are impounded by barriers of morainic debris.

The only glacial valleys that now have smoothly graded floor profiles are those which have been graded up by valley filling of postglacial date, such, for example, as the great eastern valleys of the New Zealand Alps. Aggradation of this kind is inevitable eventually in all the strictly overdeepened parts of a glacial trough and is effected rapidly where large glaciers remain and are efficiently eroding in upper valleys, supplying abundant debris to be built into "valley trains," or lower-valley aggraded plains, and indeed in every case where vigorous erosion is still in progress in valley-head regions. Beneath the thick alluvial gravels of aggraded plains, which may bury trough floors to a great depth, it may be that these rock floors are as irregular in profile as those of other valleys which are not hidden.

Irregularity of longitudinal profile beneath glaciers is a condition to be expected. Some such irregularity is no doubt homologous with that found in stream-cut valleys that are not yet graded. Icefalls, which are common features of present-day glaciers, may have been present at steep and as yet "ungraded" parts of glacier-trough floors even at the height of an ice flood. In addition, however, to such possible irregularities, it is reasonable to explain a great many, perhaps most, of the breaks of slope of rock-floor profiles as an expression of the relatively minor unevennesses of the floor beneath a thick ice stream with a graded upper surface.

Differential excavation by glaciers still ungraded is the kernel of the explanation of trough forms adopted by de Martonne, whereas

some other authors hold that the surfaces of vanished glaciers had more even gradients than the now-exposed floors of their channels.

The explanation of basin-like expansions alternating with contractions of the trough width cannot be separated from that of breaks in the longitudinal profile. Many basins are not only lateral expansions of the valley form but are also hollow-floored—being walled in on the down-valley side by rock bars ("riegels"[a])—and either still contain lakes (especially in upper valleys) or have contained lakes which have been destroyed by alluvial filling and the cutting of very young postglacial ravines through the impounding riegels. The relation of hanging side valleys to the main must also be taken into consideration.

The Glacial Stairway

The successive descents in the valley profile are generally described as "steps" (Pl. XLV, 1 and 2; Fig. 110). At each step is a more or less well-developed riegel (Pl. XLVI, 1; Figs. 111, 112),

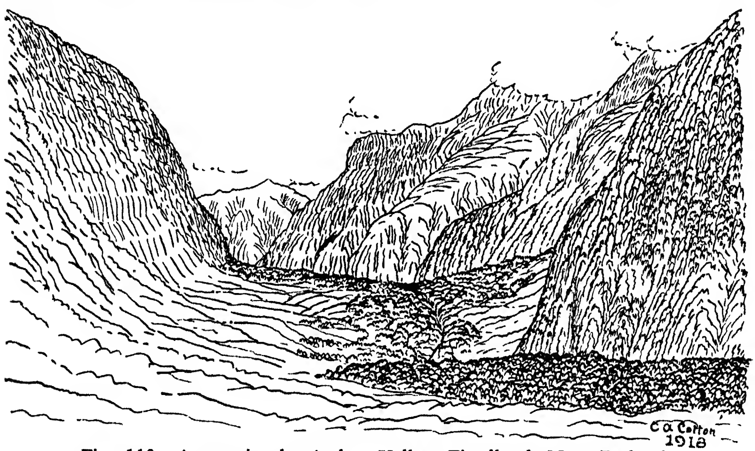

Fig. 110. A step in the Arthur Valley, Fiordland, New Zealand.

and the tread of each step may be hollowed to the concave profile of a rock-basin lake. In plan, apart from features of the floor, there may or may not be constriction of the trough at the point where the ice has passed over a riegel, but de Martonne considers that alternation of narrower, gorge-like troughs at or in the vicinity of

[a] A. Penck, Die Uebertiefung der Alpentäler, *Verh. VII Internat. Geogr. Kongr.*, p. 233, 1900.

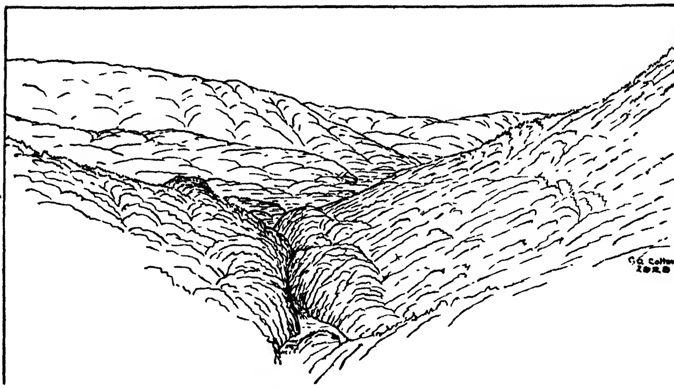

Fig. 111. Riegel and step separating an upper-valley basin (Opheim valley) at Stalheim, Norway, from a lower (Nærodal) trough. (Compare Fig. 77A.)

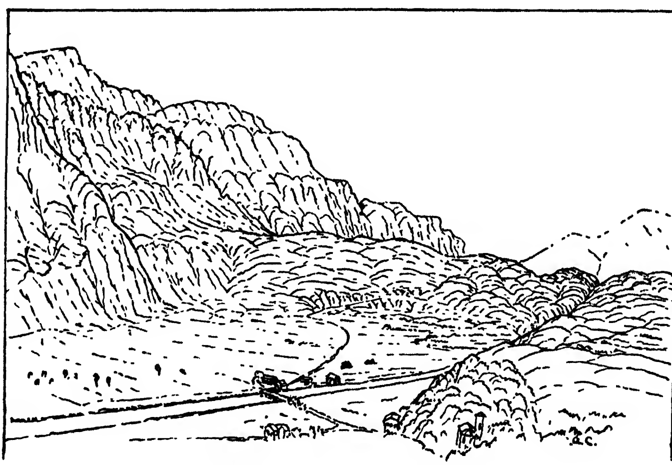

Fig. 112. The basin at Innertkirchen above the Kirchet riegel, through which is cut the deep and narrow postglacial gorge of the Aar, Switzerland.

riegels with broadly expanded basins in the reaches above or between them is typical of glacial valleys.[1] If the step-tread basins are occupied by lakes, as is commonly the case especially as valley-heads are approached, these may follow one another like beads upon a

[1] E. de Martonne, *Traité de géographie physique*, 5th ed., Fig. 348, 1935.

string—"paternoster lakes".[2] Though some of the lakes thus strung out along valley floors (Pls. XX, 2; XXXVII, 1) are held up by morainic dams, many are clearly seen to be separated by rock bars and mark the levels of successive steps on the rock floors of the valleys (Figs. 113-115). The stairway is steep at the valley head, but may continue with diminishing gradient downstream for many miles.[2a]

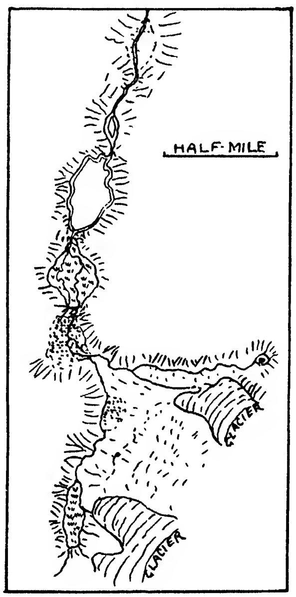

Fig. 113. Valley-head steps and paternoster lake-basins in the Avio Valley, European Alps.

Hypotheses current for the explanation of riegels and steps may be classed in two categories: those which relate them to rock structures and those which do not. It is quite probable that different explanations fit different cases, forms of somewhat different origin having as a common characteristic the strong contrast they present

[2] F. Nussbaum, Die Täler der Schweizeralpen, *Wiss. M. Schweiz. Alp. Mus. Bern,* 3, p. 28, 1910.

[2a] W. D. Johnson, The Profile of Maturity in Alpine Glacial Erosion, *Jour. Geol.,* 12, p. 570, 1904. (Quoted on p. 158.)

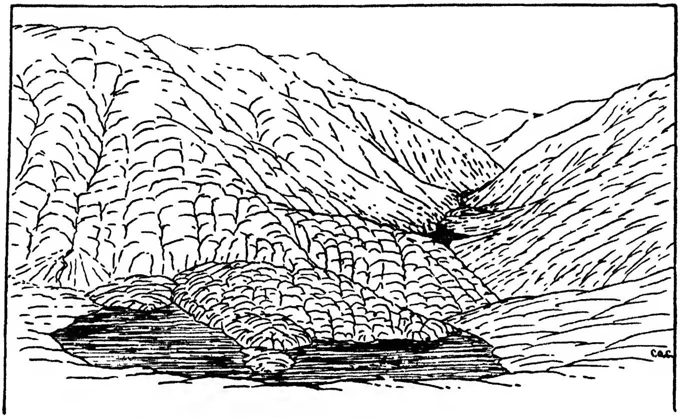

Fig. 114. Paternoster lakes, Grimsel Pass, Switzerland.

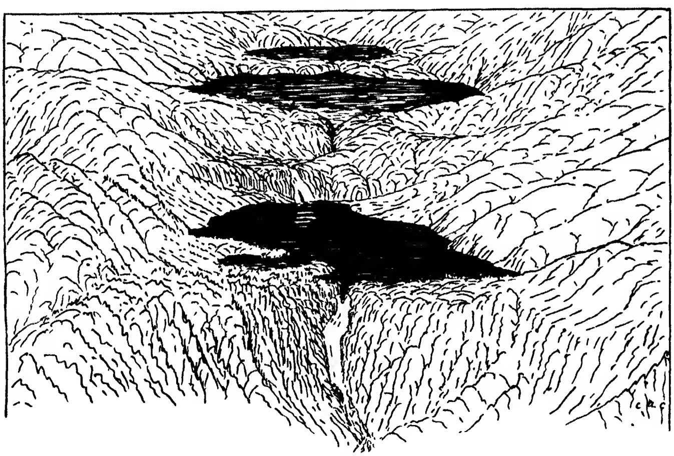

Fig. 115. Three steps and rock-basin lakes at the head of a glaciated trough, Baranof Island, Alaska. (From a photograph.)

with the normal features of normal (river-cut) valleys.[8] Some observers have noted a frequent relation of riegels in the Alps to bars of limestone formations which appear to have offered con-

[8] Such a contrast is not recognised in all cases by E. de Martonne, however (Quelques données nouvelles sur la jeunesse du relief préglaciaire dans les Alpes, *Rec. de trav. Cvijic'*, p. 125, Belgrade: 1924.

siderable resistance to erosion. On this hypothesis one must regard the rock barriers as having probably retarded preglacial normal erosion as well as glacial erosion, and the riegel, though not actually a feature inherited from the preglacial valley, may be situated at a preglacial valley constriction and may be in part the rubbed-down roots of former valley-side spurs at such a point.

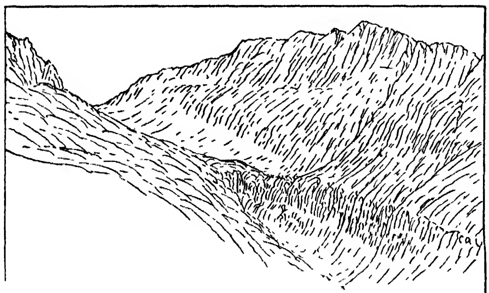

Fig. 116. Structure-controlled step in the Val Val (Aar massif); Aar granite above, paragneiss below. (Drawn from a photograph by Flückiger.)

Those who explain the trough form of the glacier channel as developed mainly by vertical glacial corrasion and derive the glaciated forms from somewhat widely opened, mature preglacial valleys must, however, regard riegels (if they are related to outcrops of resistant rock) as features that have made their appearance owing to a slower rate of glacial corrasion on the hard-rock bars than elsewhere. Such riegels are thus possibly features of valley youth in the glacial cycle—features that must disappear again if the glacier remains in existence sufficiently long to rub them down (Fig. 116).

Hypothesis of Preglacial Constrictions

According to the view of de Martonne, which he has vigorously advocated,[4] any narrowing of the preglacial valley — in some instances due to causes other than the presence of transverse hard-rock barriers—may determine the position of a riegel. The origin of the constriction might be superposition, or antecedence, or a local rejuvenation due to a capture or development of a cutoff in the course of a river. Most often, however, valley constrictions are

[4] *Loc. cit.* (1).

related to the rock structure, especially where rivers have been rejuvenated; and strong preglacial rejuvenation is a condition which de Martonne maintains must be postulated in explanation of the occurrence of riegels in glaciated valleys.[5] This he explains as the result of end-of-Tertiary upheavals which have continued and have caused repeated rejuvenations during successive interglacial epochs of normal erosion.[6] He has supported his contention by describing valley forms of the same type—i.e. a succession of more open, graded reaches separated by ungraded gorges—in the non-glaciated parts of the Var valley system in the Maritime Alps.[7]

It is an essential part of de Martonne's theory that the modification of form which preglacial valleys have undergone consists in the main of widening accompanied by a moderate amount of deepening in the basins but very little deepening on the riegels and practically no erosion on the fronts (risers) of the steps. These arguments are applicable more particularly in the explanation of the forms found in regions of moderate glaciation, where it is apparent that there has been little vertical corrasion. In the less heavily glaciated valleys on the eastern side of the New Zealand Alps, as in the case of the upper Vésubie valley in the Maritime Alps, described by de Martonne, there is a marked absence of alternating riegels and basins, and hanging valleys do not occur (with the exception of some developed from high-level cirques by headward cirque-wall sapping—p. 231); and it can be urged in explanation that the rocks of the terrain are not very resistant and that they afford, moreover, no marked alternations of relatively weak and resistant formations. Even in the more heavily glaciated districts of New Zealand, where again there is no marked alternation of weak and resistant rocks, but where very deep wall-sided troughs occur, there are indeed hanging valleys at great heights which vouch for deep trough excavation, but valley constrictions and typical basin-and-riegel alternation on a scale comparable with the grand scale of the troughs

[5] As interpreted by Ahlmann, the position of the Opheim-Nærodal step, shown in Fig. 111, has been determined by a convex nick, due to rejuvenation, in the preglacial valley profile (H. W. Ahlmann, Geomorphological Studies in Norway, *Geografiska Annaler*, 1, p. 133, 1919. As the valley forks, however, it may be correct to explain the step as an effect of glacial confluence (see p. 265).

[6] E. de Martonne, L'érosion glaciaire et la formation des vallées alpines, *Ann. de Géog.*, 19, pp. 289-317, 1910; 20, pp. 1-29, 1911.

[7] *Loc. cit.* [8].

are rare. In the Hollyford-McKerrow trough in northern Fiordland there is one very large "ex-riegel", as it may be called (Pl. XLVI, 1), which has been reduced to a pair of huge valley-side buttresses and a knob field by the excavation of an inner trough through a riegel, perhaps in the last epoch of the Glacial Period.[8] This is, however, an exceptional feature.

Thus the occurrence of the basin-and-riegel type of valley seems to be confined to certain regions, and to be related to rock structure rather than to anything else. Its presence in the Tinée and its absence from the upper Vésubie (of the Var valley system in the Maritime Alps)[9] must be a result of the structure rather than of the presence or absence of rejuvenated preglacial valley forms. This is an outcome of de Martonne's arguments, though it cannot be doubted that where an alternation of gorges and graded reaches is already present rejuvenation will develop features which require but slight modification to become riegels and basins. A test of this hypothesis as applied to the explanation of any particular landscape will be that discordance of valley junctions will be small except in those cases where the discordance can be explained as in part preglacial.

The proponents of the theory of overdeepening, to use the term in a rather unrestricted sense, explain most riegels as bars of rock either obviously more resistant than the enclosing formations or presenting specific resistance to a particular kind of erosion (in this case glacial abrasion), owing to absence of close jointing or perhaps to some less obvious property of the rock.[10] These rock bars were in the course of reduction up to the time of the disappearance of the ice, but as long as excavation continued on the more easily yielding rocks up and down the valley from them, they stood out as riegels. Only if a limit—some kind of base-level controlling valley depth—

[8] W. N. Benson and J. T. Holloway, Notes on the Geography and Rocks of the Ranges between the Pyke and Matukituki Rivers, N.W. Otago, *Trans. Roy. Soc. N.Z.*, 70, pp. 1-24, 1940.

[9] E. de Martonne has noted that the upper (glaciated) valley of the Vésubie is not only (1) above the nick or head of rejuvenation that has progressed inland in the Var system of valleys, but is also (2) in a uniformly weak terrain (*loc. cit.* [8], p. 133).

[10] "The variations of structural resistance or firmness that the searching pressure and friction of a heavy glacier could detect might be hardly recognisable to our superficial observations" (W. M. Davis, Glacial Erosion in France, Switzerland, and Norway, *Geographical Essays*, p. 662, 1909).

could be reached, then might the riegels be worn down and disappear.[11]

The problem of steps is not quite the same as that of riegels, though commonly a riegel is present at the brink of a step. Some which are related to cross-valley bars of hard rock determine steps, for the ice stream passing over a riegel-making outcrop will excavate more deeply on the weaker rocks beyond it.

De Martonne ascribes glacial erosion both vertical and lateral to corrasion by the ice stream,[12] which tends to develop for itself in easily eroded material a channel bounded by an arc of a circle. "It is above all by its weight that the glacier does its work," he asserts. Erosion, however, measured by friction between the glacier and its bedrock floor varies, he argues, not only as the cube of the thickness of the ice but also as the cosine of the angle of slope of the ice surface.[13] Erosion must be of small value, according to this formula, on a step front or on the steep down-valley slope of a riegel.

Though corrasion may be weak there is a possibility, which, though not considered by de Martonne, ought not to be lost sight of, that more or less vigorous sapping similar to that which causes cirque walls to retreat will take place on step fronts, but closely similar conditions will prevail only if the glacier descends as an ice-fall over the step and is broken by crevasses that extend to the rock floor. In the case of thick glaciers this does not seem possible, but where thin glaciers descend steps it seems highly probable that the step fronts, though protected by their steep slopes from active corrasion, are receding at an appreciable rate as a result of sapping. De Martonne believes in the existence of ground crevasses in full-bodied glaciers, or appears to do so,[14] but does not attribute any importance to a subglacial sapping process as a possible cause of

[11] It seems impossible to agree entirely with W. M. Davis, who went much farther than this and believed he recognised complete homology between "broken-bedded" glacial channels and the ungraded steep courses of young rivers. "The reaches on the weaker or more jointed rocks may be eroded during youth to a somewhat greater depth than the sill of more resistant or less-jointed rock next downstream. . . . If the glaciers had endured longer in channels of this kind, the 'rapids' and other inequalities by which the bed may be interrupted must have been worn back and lowered, and in time destroyed" (*loc. cit.* [10]).

[12] De Martonne's *"sapement"* is lateral corrasion, not "sapping" in Willard Johnson's sense.

[13] *Loc. cit.* [8], pp. 135-136.

[14] E. de Martonne, *loc. cit.* [1], Fig. 334.

headward retreat of steps. He regards the steps, on the contrary, as remaining fixed in position, whether related to bars of hard rock or not.

Another subglacial erosive process which must not be ignored is plucking, of which there is evidence on the down-valley slopes of some steps and riegels and of the various knobs and prominences that have been overswept by ice. The ice freezes to loosely held joint-bounded blocks of rock (water passing readily into ice at the freezing temperature wherever tension is developed—p. 146) and the blocks are dragged away, and even rock that is free from cracks or flaws may be torn apart in some cases (p. 177). The adhesion of ice to rock under a glacier will vary, according to de Martonne,[15] inversely as the tangent of the slope of the ice surface, but the field evidence that plucking has taken place in situations where the rock floor slopes steeply down-valley is incontrovertible. The effects of abrasion being in such circumstances at a minimum, it may be that here a very moderate amount of plucking has left a visible result, whereas the results of more efficient plucking on other surfaces have been obliterated by powerful scour. Except under thin glaciers (where sapping of steps may occur) the riegel, or the step without a riegel, may perhaps, therefore, be a very stable form scarcely subject to attack from the down-valley side.

The contention of de Martonne that preglacial stream erosion has been responsible for the production of the initial forms of basins and riegels, the work of glaciers adding only the finishing touches, has been supported by Sölch,[16] who, however, goes farther and enlists the support of English and French advocates of glacial protection and of erosion by subglacial streams. He quotes with approval phrases applied by Harker to glacial features in Skye, such as that ice-work had given "final touches" to the forms and had been responsible only for "actual details." The more recent description of the glaciated hills of Skye given by Lewis,[17] however, suggests that such phrases in descriptions written forty years ago

[15] *Loc. cit.* (8), p. 136.

[16] J. Sölch, Fluss- und Eiswerk in den Alpen, *Pet. Mitt. Ergänz.*, 219 and 220, 1935.

[17] W. V. Lewis, A Melt-water Hypothesis of Cirque Formation, *Geol. Mag.*, 75, pp. 249-265, 1938.

were more often than not introduced as concessions to the mood of extreme caution and scepticism regarding any theory of deep glacial erosion then prevailing.

The extreme argument that riegels are entirely of preglacial development has been advanced by Garwood[18] and applied in particular to features of the floor of the Valle Leventina (Ticino or Tessin valley) in the Alps, which he has interpreted as existing prior to the last glaciation in their present form with the exception of a

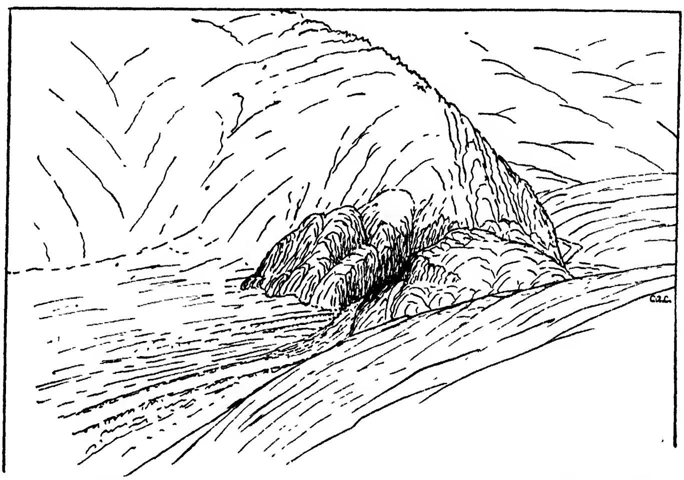

Fig. 117. A riegel below Airolo, traversed by a postglacial gorge of the Ticino. (Drawn from a photograph by E. J. Garwood.)

very small amount of rounding and smoothing of rock bars by ice-work during that ice flood. According to Garwood's theory the valley had recently been rejuvenated by erosion following upheaval but opened out as basins in graded reaches, these being separated by gorges through riegels essentially as they are to-day. (In his account of the origin of the features of the valley Garwood uses "overdeepening" not in Penck's sense but as meaning "rejuvenation.") Not only the alternation of basins and riegels but also the cutting of gorges through the riegels (obviously postglacial river-work, according to the views of most observers—see Fig. 117) are

[18] E. J. Garwood, On the Origin of Some Hanging Valleys in the Alps and Himalayas, *Quart. Jour. Geol. Soc.*, 58, pp. 703-718, 1902.

attributed to an epoch anterior to the last glaciation. The theory could not be extended to cover the case of basins containing rock-rimmed lakes without a further assumption that strong differential deepening had occurred at a late date.

The much older theory of Freshfield[19] attributes the gorge through a riegel neither to postglacial nor preglacial, but to subglacial stream-work. Unless, however, it be postulated that the erosion of basins took place contemporaneously and to a like depth—to a great width also—as a result of the erosive work of water beneath a glacier the argument stultifies itself if urged, as it has been, as part of a theory that ice does not erode.

The theory of preglacial origin of steps implies that most of them occur either in heterogeneous terrains at the points where the more resistant members have held up preglacial rivers in ungraded gorges, or in localities where successive rejuvenation nicks have been following one another up the valleys of preglacial rivers. The latter alternative is favoured by Sölch.

Hypothesis of Overdeepening

The hypothesis of overdeepening, as applied to the origin of steps and of riegel-and-basin valley forms, has been advocated especially by Penck[20] but has been consistently favoured also by Davis in his many descriptions of glaciated features. Gilbert, though a believer in the power of an ice stream to make deep excavations, did not make specific application of the theory of vertical corrasion to this particular problem.

The overdeepening hypothesis attempts to explain some riegels (and necessarily the steps associated with these) as fixed in position and thus somewhat stable features in the glacial cycle, in that they are rooted on hard-rock bars. Most steps are considered stable forms by the advocates of the hypothesis, however, for a different reason. A cascading or stepped glacier-surface profile, regarded by de Martonne as stable, is in reality an ephemeral form of youth, or, where found, as it very commonly is, in the shrunken glaciers of the present

[19] D. W. Freshfield, Note on the Conservative Action of Glaciers, *Proc. Roy. Geog. Soc.*, 10, pp. 785-787, 1888.

[20] A. Penck, Die Uebertiefung der Alpentäler, *Verh. VII Internat. Geog. Kongr.* pp. 232-240, 1900; Glacial Features in the Surface of the Alps, *Jour. Geol.*, 13, pp. 1-17, 1905.

day, gives no indication of what glacier surfaces were as they existed at the height of an ice flood, to which it is assumed that floor profiles were adjusted. Steps in the rock floor, therefore, are necessary elements of the profile of maturity beneath glaciers with graded surface slopes, just as a step down to the main floor from the mouth of a hanging valley exists normally beneath glaciers with accordant junctions.

This principle is embodied in Penck's "law of adjusted cross-sections,"[21] which is applicable to streams whether of ice or water. "If there is no sudden change in the velocity of the moving bodies—those changes will always disappear in the course of time—or in the precipitation and evaporation or ablation of a certain region, the neighbouring cross-sections will increase in the same way as the areas do." In conjunction with the circumstance that glacial erosion is selective, i.e. governed to some extent by the nature of the rocks of the terrain, the law of cross-sections may account for the variation of transverse profile from a broad and shallow to a narrow and deep form where a rock boundary is crossed. Thus "many steps in glacial valleys are caused by highly resistant rocks".[21]

Confluence of secondary glaciers and diffluence, where distributary glaciers leave the main, are responsible, however, for abrupt accessions and diminutions of volume, enlargements and shrinkages of the cross-section of the glacier; and at such points the cross-section law requires generally a deepening or shallowing of the main trough. The latter is important in connection with the theory of the origin of lake basins, while abrupt deepening, forming "steps of confluence," has expression not only in the hanging mouth of a side valley but also in a step in the floor of a main valley, more or less pronounced according to the ratio of the sections of tributary and main and the opportunity the trunk glacier may have had to increase its section by widening as well as deepening below the confluence. The step down from the Opheim valley to the greatly deepened Nærodal trough, Norway (Fig. 111), for example, occurs at a point of confluence (compare Fig. 77A); and so also do those

[21] *Loc. cit.* [20], 1905. ($VQ = A(p\text{-}e)$; where V = mean velocity of the stream (ice or water), Q = cross section, A = area of catchment basin, p = precipitation, and e = evaporation or ablation.)

descending to the floors of basins submerged beneath the waters of fiords in Norway and Greenland.[22]

Convergent Cirques and the Trough-end

The law of adjusted cross-sections does not very satisfactorily explain all the peculiar features of glaciated valleys; the alternation of riegel and basin seems most often related to structure, and some other explanation may have to be found for steep stairways near the heads of some valleys. A single, very pronounced step in the upper valley, however, which is regarded by Penck as marking the end of the trough or channel occupied by the glacier tongue, finds a most credible explanation in the cross-section theory. This feature, by no means universally present,[23] though considered by Penck as one of the characteristic features of glaciated mountain regions, is found fully and typically developed where a valley glacier is fed at the head with firn from a cluster of converging cirques so that it has a broadly expanded head névé. The name applied to the imposing trough-head step by Penck[24] is "trough's end," for which one might substitute "trough-end" or von Engeln's[25] term "cross wall." It cannot be doubted that an imposing trough-end cliff exists beneath both the Fox and Franz Josef Glaciers (in New Zealand) at the points where the ice from their broad névés is gathered into narrow streams (Pl. XI, 1). A trough-end in a deeply-excavated Swiss glacial valley is shown in Fig. 118, and the essential features of an expanded valley-head are presented in a diagram as Fig. 119. The confluent ice from converging cirques has been concentrated in a narrower and necessarily deeper channel below the trough-end.

At such a confluence, which may be assumed to have been a result of the preglacial landscape form, "in order to maintain a continuous movement an increase of velocity was necessary . . . This

[22] A. Helland, On the Ice Fjords of Norway and Greenland, *Quart. Jour. Geol. Soc.*, 33, p. 174, 1877; H. W. Ahlmann, Geomorphological Studies in Norway, *Geografiska Annaler*, 1, pp. 1-148, 193-252, 1919; N. E. Odell, The Glaciers and Morphology of the Franz Josef Fjord Region of North-east Greenland, *Geog. Jour.*, 90, pp. 111-125, 233-258, 1937.

[23] It is rarely found in the Fiordland troughs of New Zealand or in those of Norway (H. W. Ahlmann, Geomorphological Studies in Norway, *Geografiska Annaler*, 1, p. 75, 1919).

[24] A. Penck, *loc. cit.* (20), 1905, p. 2.

[25] O. D. von Engeln, Palisade Glacier, *Bull. Geol. Soc. Am.*, 44, pp. 575-600, 1933.

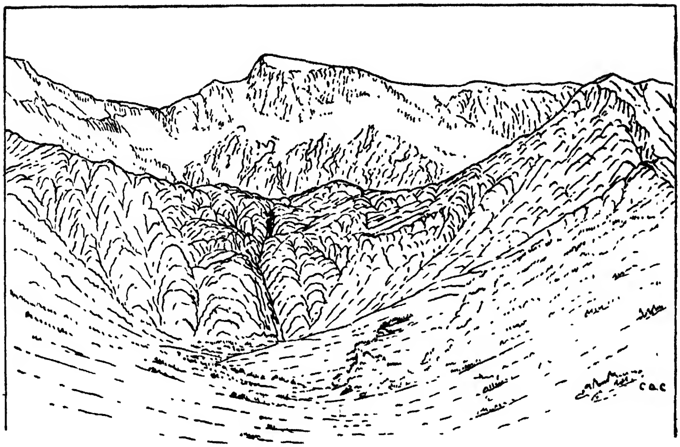

Fig. 118. Step, or trough-end, 1,500 feet high, separating the head of the Adelboden trough (Switzerland) from a valley-head cirque above it.

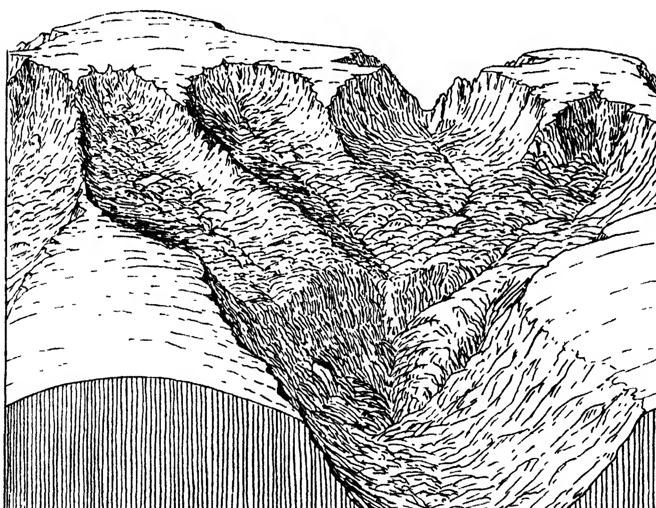

Fig. 119. A valley-head step (trough-end), above which is a cluster of convergent cirques. (Based on a diagram by Davis.)

increased velocity must act on the bed of the glaciers until a sufficient depth is attained. Theoretically this depth must be 57 per cent (that is $\frac{\pi}{2} - 1$) greater than that at the semicircle from which the glaciers came."[26]

This theory that typical trough-ends are related to glacial confluence seems preferable to that of de Martonne which relates them to rejuvenation nicks in preglacial stream profiles little modified by glacial erosion. From the latter point of view, though the preglacial longitudinal profile might be regarded as but little modified, very great lateral enlargement of the head of the trough must be assumed immediately below the step, sufficient to convert a postulated preglacial narrow ravine head into a great amphitheatre. Such a form is found, indeed, immediately below most valley steps and riegels, where the valley has been broadly opened out to a trough or U form closely simulating that just above the step, which, according to de Martonne's theory is that of a more wide-open reach of the preglacial valley only slightly modified.

Hypothesis of Subglacial Sapping

As noted on an earlier page, it seems scarcely possible that ground crevasses can exist in thick glaciers or that vigorous subglacial sapping such as might be related to freeze-and-thaw effects under open crevasses can have contributed appreciably to step-development under such glaciers. Under thin glaciers, especially towards valley-heads, where preglacial gradients were presumably steep and infantile glaciers had broken surfaces, quite possibly conditions favoured development of steps by sapping, which would cause headward retreat and accentuation of initial declivities analogous to the development of autogenetic[27] falls by plunge-pool back-scour in the valleys of some young rivers. This process, in combination with some corrasion on the treads of steps, may be sufficient to account for the presence of the characteristic strings of paternoster lakes towards some glacial valley-heads. The cause of such local overdeepening, which is of more general occurrence than the alternating basin-and-riegel form in lower valleys, and is found where the rocks of the terrain are of uniform character according

[26] A. Penck, *loc. cit.* (20), 1905, p. 9.
[27] W. M. Davis, *Bull. Geol. Soc. Am.*, 43, p. 438, 1932.

to ordinary standards, must be sought for in differences in the joint pattern or something else in the texture of the rocks influencing the selective power of glacial corrasion.[28] Even the large-scale features of the Yosemite canyon are attributed by Matthes[29] to absence and presence of abundant joints in different parts of a granite terrain. By-products, however, of this theory are (1) that efficiency of glacial corrasion depends almost entirely on a glacier's ability to pluck, and (2) that steps are rooted on the structure and are thus not free to migrate up-valley.

The hypothesis of autogenetic step-development by accentuation of small initial breaks of slope has been worded as follows by T. C. and R. T. Chamberlin:[30]

> If a pre-existent step or down-set crosses the bottom of the valley at any point beneath a glacier, or if a step is developed by structural inequalities, and if the down-set is sufficiently great in proportion to the thickness of the ice to cause effective crevassing through the whole depth of the glacier, the conditions at the base of the step are not radically different from those at the base of the cirque wall, for there is in effect a break in the continuity of the motion of the glacier, and the beginning of a new motion in the ice mass below. The rock face of the step may be regarded as a cirque wall in a modified sense. From it masses may be detached and, falling against the ice wall, become attached and dragged forward . . . Sapping and stoping seem to be rather general phenomena of the basal action of glaciers. The operation of the stoping process at several points in a long glacier tongue, by developing successive ice falls between more or less level stretches, results in a rude stairway of giant tread.

Although starting with the same premise of initial inequalities of profile, this hypothesis is radically different from that of de Martonne, for steps developed by sapping are not stationary but must

[28] According to an early theory put forward by de Martonne, which he regarded afterwards as secondary or alternative to his preferred theory of mechanical corrasion controlled by initial slopes, upper valley steps (or steps in a cirque stairway) mark the positions of glacier terminals during halts in a retreat, or their positions in successive glacial epochs, and basins have been hollowed out under thicker parts not far behind rather steep glacier snouts during each halt (*loc. cit.* [6], p. 313).

[29] F. E. Matthes, Geologic History of the Yosemite Valley, *U.S. Geol. Surv. Prof. Paper*, 160, 1930.

[30] Certain Phases of Glacial Erosion, *Jour. Geol.*, 19, pp. 213-4, 1911.

continue to retreat up-valley as long as sapping is active. Steps originating thus, and probably increasing in height so as to become very conspicuous landscape forms if the glacier covering them melts away soon enough, must, however, be ephemeral features of the trough profile under continuous glaciation and must eventually be merged into the wall of the valley-head cirque, into the trough-end, or into the wall of some other step controlled in a mature profile by ice-stream cross-sections, according to Penck's theory. Troughs that do not receive tributaries (do not branch) must develop stepless floors like that which may be present under the Galiano Glacier in Alaska, and like that possibly present beneath alluvial filling in the Clinton Canyon in New Zealand, but the glacier in the latter must have been thousands of feet deep, much too deep for ground crevasses.

According to Ahlmann[31] "the great cirque stairways on . . . the Lofoten Islands tell unmistakably in favour of the idea that ice enlarged and intensified the initial unevenness. This also holds good of the greater valleys in the rest of Norway, which in pre-glacial times were probably in youth and which were transformed by the ice into their present broken-bedded form."

Hypothesis of Headward Glacial Erosion

Yet another hypothesis emerges as a corollary of the theory of headward glacial erosion advocated especially by Willard Johnson[32] and by Taylor[33] (Chapter XV). Johnson credited sapping with a great deal more than the development of the imposing back walls of cirques. According to his view, in some cases during the development of a high valley-head wall by the sapping process the head wall "breaks back into steps successively shortening in length of tread. The rearward steps may continue to be marked by schrunds rising to the glacier surface; living glaciers in fact are often characterised by 'cascades' in their upper courses."

[31] H. W. Ahlmann, Geomorphological Studies in Norway, *Geografiska Annaler*, 1, p. 242, 1919.

[32] Willard D. Johnson, The Profile of Maturity in Alpine Glacial Erosion, *Jour. Geol.*, 12, pp. 569-578, 1904.

[33] Griffith Taylor, Physiography and Glacial Geology of East Antarctica, *Geog. Jour.*, 44, p. 365-382, 452-467, 553-571, 1914.

This implies that not only the valley-head cirque but the glacial trough also (or a part of it at least) has been developed by headward erosion, and step-making is incidental to this process. Those steps (earliest formed) which remain farthest down-valley under the glacier being no longer so vigorously sapped become less sharply defined under the "dulling influence of scour."

The "palimpsest" theory of Taylor[34] is a variant of Johnson's hypothesis, in which he supposes a stairway of cirques to have been developed by isolated glaciers and afterwards modified by a stream of continuous ice. This has rounded off the rock bars between cirques, converting them into typical riegels and steps. So he explains the great Nussbaum riegel, in Antarctica.

It is a part of Johnson's hypothesis that at least the later formed steps, though outpaced by a rapidly sapped valley-head cirque-wall, may still be migrating headward. It is noteworthy, however, that the migration of steps progressively abandoned by the glacier as valley heads as its head wall "breaks back" with development of ever newer cirques in a continuous stairway implies the reverse of von Engeln's conception of steps following one another in up-valley retreat until they are eliminated from the profile, even though von Engeln admits that a stern chase is a long one.[35] Johnson's hypothesis has this advantage over Chamberlin's and von Engeln's hypotheses of subglacial sapping that it does not have to postulate in regions like the High Sierra of California the existence of distinctly nicked stream profiles in the preglacial epoch. On the other hand, it rules out the possibility—probability indeed—that some, if not most, stepped glacial troughs are developed from stream valleys by processes of glacial erosion in which abrasion and some form of subglacial sapping may both take part.

[34] Griffith Taylor, *loc. cit.* (33).
[35] O. D. von Engeln, *loc. cit.* (25), p. 595.

CHAPTER XX

Piedmont Lakes and Fiords

A FURTHER problem concerning the subglacial profiles of glacial channels is that of the origin of the basins now occupied by piedmont lakes, and another closely related question concerns the origin of fiords. Both in typical piedmont lakes lying in deep valleys that bear the marks of glacial occupation and in most true fiords, which also present evidence of glaciation, there are long reversed slopes on the rock floors. Thus the valleys they occupy are "rock basins", and a lowering of sea-level would convert these fiords into lakes which would still be of great depth.[1] Undoubtedly great elongated rock basins exist also in many valleys which are no longer occupied by lakes, being filled instead with lake silts and deltaic deposits, which are buried in their turn in some cases under the thick gravels of aggraded valley plains. Both the rock thresholds in the valley mouths and the lake fillings may be trenched and revealed by later erosion, as is the case for example in the Rakaia Valley, in New Zealand.

It is observed in many cases that the actual levels of lakes are maintained by obstructions formed by landslides, by alluvial fans built by side streams, and by great morainic barriers of jettisoned glacial debris in glacier troughs. So also have the thresholds of fiords (which are characteristically deeper within) been built up in part by deposits of morainic debris.[2] (A morainic bar of this nature stands above sea-level in the Blackstone Bay fiord, in Alaska.[3]) It is obvious, however, in the case of many glacial-valley lakes that the deposited obstructions have merely raised the levels and slightly increased the areas of lakes which would in their absence still occupy deep basins behind bedrock thresholds, and it cannot be doubted that the majority of fiords also have rock

[1] "If Norway and the bottom of the German Ocean were elevated together, its fiords on the whole would become long and deep lakes." (A. Helland, On the Ice Fjords . . . , *Quart. Jour. Geol. Soc.*, 33, p. 172, 1877.)

[2] A. Helland, On the Ice Fjords of Norway and Greenland, *Quart. Jour. Geol. Soc.*, 33, pp. 174-5, 1877.

[3] R. S. Tarr, *College Physiography*, Fig. 156, 1914.

thresholds. Many rock-basin lakes have floors far below sea-level.[4] Both Lakes Wakatipu (Pl. XLVI, 2) and Te Anau (Pl. XXXVIII, 1), in New Zealand, for example, have floors 227 feet below the sea in their deepest part, and that of Lake Manapouri (Pl. XXXV, 1) is 859 feet below.

Steps and hanging valleys concealed beneath the waters of lakes and fiords are revealed by soundings and their presence is consistent with the glacial explanation of the valleys in which they lie; but the immediate problem is a long and strong reversed slope in the longitudinal profile of the floor.

The Theory of Warping

Special theories of reversal of valley slopes by earth movements, which might locally affect either glaciated or normal valley profiles, have been put forward—notably, for example, Heim's[5] theory that a general movement of warping in the Alpine region reversed valley slopes so as to form the European piedmont lakes in the first interglacial epoch. Advocacy of such theories has given way, however, to a very general agreement that the reverse slopes under piedmont lakes (and fiords also) were originally developed in their present attitudes by erosion, and the only erosion hypothesis admissible for their explanation is that of erosion under the deepest ice of thick glaciers—erosion, as is generally allowed, being greatest where the ice is thickest.

Near the terminal face not only does a glacier dwindle and become thin, but as more and more melt-water is formed at the expense of the ice the velocity also dwindles and the ice has little power to erode. Thus it is not difficult to see why the bedrock floor ascends in the down-valley direction, as though the diminution of cross-section of the ice stream must be accommodated by an inclined ascent of the under surface as well as the down-valley descent of the upper surface, which must of course be maintained also if the glacier is to continue to flow, and which will persist as long as alimentation continues at the head of the glacier.[6]

[4] A. Penck, *Morphologie der Erdoberfläche*, 2, p. 322, 1894.

[5] A. Heim, Die Entstehung der alpinen Randseen, *Vierteljahrsschr. d. Naturf. Ges.* Zürich, 39, 1894.

[6] W. M. Davis, Glacial Erosion in France, Switzerland, and Norway, *Proc. Boston Soc. Nat. Hist.*, 29, pp. 273-322, 1900; reprinted *Geographical Essays*, p. 668.

The problem presented by the deep basins of Alpine piedmont lakes attracted attention long before other features due to glaciation had been thoroughly studied, and their deepening was attributed to glacial erosion by Ramsay.[7] It was not until many years later, however, that the rival warping and glacial hypotheses were put

Fig. 120. A lake without branches or lateral embayments in a wall-sided glacial trough (Komaktorvik Lake, Northern Labrador). (From a photograph.)

to the test of confrontation with their deduced consequences. The absence of embayments along the wall-like sides of piedmont lakes (Fig. 120) not only suggests that the lakes lie in deepened (overdeepened) glacial channels but also disproves the warping theory; for warping cannot affect a main valley alone. The tributaries and the surroundings generally of a down-warped portion

[7] A. C. Ramsay, On the Glacial Erosion of Certain Lakes in Switzerland, *Quart. Jour. Geol. Soc.*, 18, p. 185, 1862.

of a normal valley must be depressed with it, so that a lake formed by warping may be expected to thrust out arms into depressed side valleys. It was recognition of the absence of such embayments that enabled Wallace[8] to demonstrate that the warping theory was inadequate to explain piedmont lakes in competition with the theory of glacial deepening, for the latter has proceeded (in many cases) without affecting side valleys.

As pointed out by Penck,[9] branching piedmont lakes are exemplified in northern Italy, but the branching takes place there as a result of submergence of the junctions not of tributary valleys

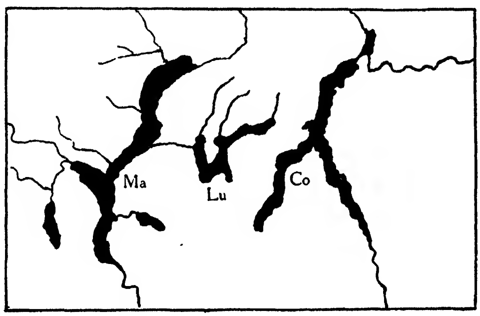

Fig. 121. Piedmont lakes of Northern Italy. Co, Como; Lu, Lugano; Ma, Maggiore.

but of distributaries formed by glacial diffluence. In only a few of the many cases of diffluence, however, is there close enough accordance of level between the floors of diverging distributary glacier channels to produce a perfect bifurcation like that of Lake Como (Fig. 121), where the two glacial outlets have been of approximately equal cross-sections.

Overdeepening

The theory of overdeepening as applied to the excavation of rock basins in glacier troughs has been expressed by Penck as follows:

> In a simple glacier the maximum cross-section will be found just at the snow-line; in a composite one it may occur farther

[8] A. R. Wallace, The Ice Age and its Work, *Fortnightly Review,* 60, pp. 616-33, 750-74, 1893.

[9] A. Penck, Glacial Features in the Surface of the Alps, *Jour. Geol.,* 13, p. 11, 1905.

> downward. Above and below this maximum cross-section the surfaces and bottoms of the cross-sections will approach one another until they finally coalesce. While, however, the surfaces must be arranged in a descending order, the same is not the case with the bottom. It is stated from observation that glaciers can also move on reversed slopes as long as they have a sufficient surface slope; that is, as long as the surface slope is considerably greater than the reversed bottom slope. To keep up glacial movement, it is necessary that the centres of successive cross-sections be arranged in a descending order. If we, therefore, have, at the lower end of a glacier, a series of cross-sections of diminishing size, their bottoms may rise, if their surfaces slope so steeply that their centres of gravity form a continually descending line. Therefore we find in the bottoms of glaciated valleys reversed slopes, and we must expect to find them chiefly near the ends of the old glaciers.[10]

If, as a result of glacier wastage in a waning phase of the glacierisation of a region, the centres of gravity of successive cross-sections failed to "form a continuously descending line" it would appear that the ice would fail to move as a whole, and a bottom layer would become stagnant beneath a superficial stream. At such a stage of deglacierisation it might be possible to agree with one of the last dissentients from the doctrine of glacial erosion that "there was probably a lens of stationary ice in the bottom of the Wakatipu trough . . . over which the moving portion of the Wakatipu glacier slid",[11] though the suggestion when it was made was intended to apply to the whole ice-flood epoch, during most of which, glacialists are convinced, the floor of the trough was subject to intense abrasion under the sole of the ice stream.

Fiords

In any discussion of the origin of fiords pseudo-fiords must be excluded and attention must be confined to deep arms of the sea which bear the marks of glacial occupation and at least some excavation and enlargement by glacial erosion. Most of these, especially those that are narrow and high-walled as well as deep,

[10] A. Penck, The Valleys and Lakes of the Alps, *Rep. VIII Internat. Geog. Cong.*, pp. 173-184, 1905; *loc. cit.* (9), pp. 7-8.

[11] H. T. Ferrar, Pleistocene Glaciation of Central Otago, *Trans. N.Z. Inst.*, 59, p. 619, 1928.

are separated from the ocean by relatively shallow thresholds. The problem of the origin of such valleys which the sea has entered becomes almost exactly the same as that of the origin of piedmont lakes. The relatively shallow thresholds, contrasting with water of enormous depth[12] (in some cases about 4000 feet) within the entrances bring most fiords into the category of valleys which undoubtedly have reverse slopes on their bedrock floors. No simple theory of drowning by submergence of normal valleys will fit them, nor will it serve to differentiate them from piedmont lakes, for a reversal of such postulated submergence would merely convert fiords into piedmont lakes (p. 272).

The question whether the glaciers which occupied valleys that have become fiords eroded them to their present depth below sea-level[13] remains to be considered, however, for there is a persistent tendency among geographers to class fiords along with rias as coastal features due to land submergence and to differentiate them only as drowned glacial valleys. Parts at least of some fiord-indented regions, notably Scandinavia, Spitsbergen, and Northern Labrador, exhibit abundant shoreline evidence of extensive uplift and little or no unequivocal evidence of land submergence, and so the conclusion must be drawn that very thick glaciers flowing to the sea have excavated their trough floors far below sea-level. Gilbert[14] has discussed the question whether the weight with which glaciers press upon so as to abrade their floors is lessened by the buoyancy of the sea-water in which they may perhaps be considered to be bathed. The conclusion he arrives at is that there will not be any buoyant effect, but that partially submerged glaciers will press as heavily on their floors as glaciers of the same thickness would

[12] Helland has recorded that Sognefjord, Norway, is at one place 1,244 metres deep, while at the entrance the depth is only 158 metres and at a distance of 100 kilometres out at sea only 124 metres (*loc. cit.*, p. 175). Ahlmann states that the "great mouth threshold consists of solid rock. . . . Sognefjord is a single gigantic rock basin" (H. W. Ahlmann Geomorphological Studies in Norway, *Geografiska Annaler*, 1, p. 135, 1919). Early records of the discovery of fiord thresholds and of great depth of water within fiords were made by James Cook (*Voyages*), who sounded the entrances to Dusky Bay, New Zealand, in March, 1773, and to Christmas Sound (now Cook Bay), Patagonia, in December, 1774.

[13] See N. S. Shaler, Evidences as to Changes of Sea-level, *Bull. Geol. Soc. Am.*, 6, pp. 141-166, 1895.

[14] G. K. Gilbert, Glaciers, *Harriman Alaska Expedition*, 3, pp. 210-218, 1903.

do inland. Nansen has similarly concluded that unless partial submergence reduces the velocity of its movement "a glacier will have the same erosive effect upon the underlying ground, whether above or below sea-level, down to a depth below the latter equal to nearly nine-tenths of the thickness of the ice, at which depth the glacier begins to float and is lifted from the sea floor."[15] Whether this verdict is or is not justified, there can be little doubt that thick glaciers have excavated the floors of fiords to depths far below sea-level. The process of glacial excavation of fiords was clearly envisaged by Helland, who described it as follows:

> When thick glaciers descended into the fiords and constantly deepened their beds, very peculiar relations of depth would be caused in the fiords. The glacier of the main fiord was constantly increased on its way by supply from tributary fiords, in consequence of which the depth or breadth of the fiord must have been increased. As the glacier proceeded further down the fiord the loss from melting would exceed the supply from the sides; and thus its erosive power, and consequently the depth of the fiord, would decrease; but while the glaciers deepened the bottom of the fiords, the depth of the sea in front of them would be diminished, as all the detritus would be deposited there.[16]

Relation of Fiords to Structure

Some angular patterns in the networks made by fiords and their branches and intercommunicating straits (Figs. 122, 123) are interpreted as showing a close relationship to fracture systems in the terrain. In so far as such patterns are made up in reality of intersecting systems of parallel earth lineaments it appears that the normal preglacial valleys which provided channels for the glaciers of the ice flood (with their secondaries and distributaries) had been guided themselves in their headward erosional development by crushed zones or other structural planes of weakness of such regularity and continuity as to constitute lineaments that would control the valley and stream pattern. Thus it has been written of the fiords and valleys of West Greenland:

[15] F. Nansen, Strandflat and Isostasy, *Vidensk. Skr., M.-N. Kl. 1921*, 11, p. 23, 1922.

[16] A. Helland, *loc. cit.* (1), p. 174. This statement embodies the principle afterwards named by Penck the "law of adjusted cross-sections" (see p. 265).

All of the valleys that were studied in detail proved to coincide with either dykes or faults, or both. . . . Since all the valleys are straight or angular, it seems probable that faulting and intrusion have been of primary importance in determining the drainage pattern of the area.[17]

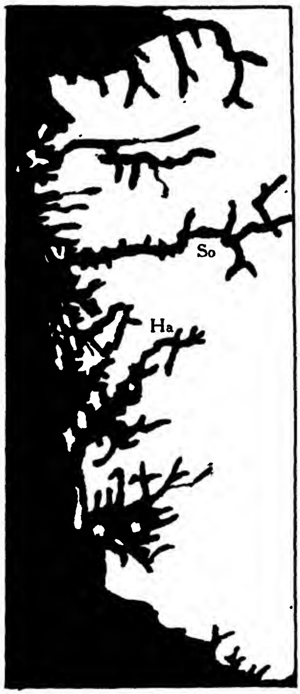

Fig. 122. The fiord pattern of western Norway. Ha, Hardangerfjord; So, Sognefjord.

Those fiords which present unique "fiord" characteristics, such as near-vertical walls thousands of feet in height and depth (Pls. XXII, 2; XLVII, 1; XLVIII, 1) associated with narrow outlets to the sea and deeply eroded rock-basin floors, features which differentiate them very sharply from most drowned normal valleys, are, as Nansen has noted, those which transect terrains of "hard and resistant Archaean and igneous rocks in western Norway and in

[17] M. Demorest, Glaciation of the Upper Nugssuak Peninsula, W. Greenland, *Zeits. f. Gletscherk.*, 25, p. 41, 1937.

Greenland", and, one may add, other regions, including south-western New Zealand (Figs. 123, 124). In such terrains fiords are "narrow, deep, and often winding," being perhaps guided by fracture zones. These forms have resulted from the confinement of

Fig. 123. Fiords and piedmont lakes of South-western New Zealand: H, Hawea Lake; Ma, Manapouri Lake; Mi, Milford Sound; T, Te Anau Lake; W, Wakatipu Lake; Wa, Wanaka Lake.

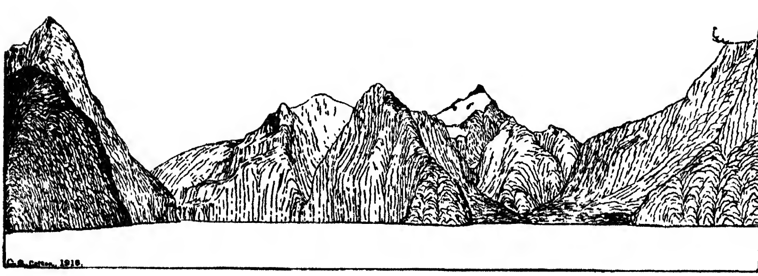

Fig. 124. Milford Sound, a New Zealand fiord.

rapid-moving ice streams to narrow, perhaps already deep, but soon greatly deepened, preglacial river valleys. It is in these terrains that preglacial river valleys guided by lineaments and exhibiting sharp angular and rectangular elbows may be expected to occur.

Contrasting with these deep, narrow, and often zigzag fiords those in regions of less resistant rocks are relatively shallow and wide and become wider towards the mouths, as is the case in Iceland and northern Norway. According to Nansen's view, in such terrains "the initial preglacial valleys were broader, the glaciers would be more able to take their own course, and their erosion would not be so exclusively vertical, but also to some extent horizontal, especially because the mountain slopes on their sides were much more rapidly destroyed by frost. The glaciers would thus widen out, be less deep, and would obtain much smaller velocities."[18]

Theory of Tectonic-trough Origin

The apparent relation of some fiord trends to landscape lineaments such as are developed along lines of faulting in the terrain is the chief argument that has been relied on in support of a now outworn theory of tectonic origin of fiords.

It is of course eminently possible that some true fiords, or parts of true fiords, as well as piedmont lakes, which have been mainly shaped and certainly deepened by glacial erosion, have had as their initial forms fault-angles, grabens, or sharply downwarped troughs only slightly modified by normal processes in a preglacial cycle. Such is believed to have been the case, for example, in the main basins of Lakes Te Anau and Manapouri, New Zealand (Fig. 123), though probably not in the more fiordlike western arms of Te Anau (Pl. XXXVIII, 1).; and there has been some suggestion of a tectonic origin also for the preglacial valley that has been converted into the wall-sided fiord-like Lake Wakatipu.[19]

That, however, is as far as the tectonic theory of fiord origin can be supported with any confidence, notwithstanding a bulky volume of special pleading in its favour.[20] Bluntly stated in the

[18] F. Nansen, *loc. cit.* (15), p. 22.

[19] W. N. Benson, Some Landforms in Southern New Zealand, *Australian Geographer*, 2, 1935.

[20] J. W. Gregory, *The Nature and Origin of Fiords*, 1913; D. W. Johnson, The Nature and Origin of Fiords (review), *Science*, 41, pp. 537-543, 1915.

words of Johnson,[21] the tectonic theory of fiords is the theory which regards "every fiord as either a gaping chasm or a rift valley formed by the dropping down of a narrow strip of the earth's crust between two parallel faults," a theory "once much in vogue as an explanation for all valleys." Johnson has added: "Whereas, according to the glacial theory, many fiords may be located along fault lines or joints, according to the tectonic theory *every* fiord must be so located." The tectonic theory has pressed into its service, to do duty as "fiords", rias and other deeply indented shorelines in all latitudes. Among these pseudo-fiords the drowned valleys in trellised pattern in the structurally-adjusted landscape of the Dalmatian coast have been included and have been made to appear as tectonic features, being documented by an imagined fault scarp in the Bay of Cattaro.

Many geologists who have mistakenly described pseudo-tectonic as tectonic landscape forms have failed to think clearly on the distinction between fault features of the landscape which are really of tectonic origin and purely erosional features guided by faults, which latter are in some cases very ancient—the so-called "fault-line" features. The fact that valleys and scarps in these two widely separate categories are insufficiently distinguished in the accepted nomenclature as "fault" and "fault-line" features is not an adequate excuse for this geomorphic crime.

Holtedahl has made important observations on the angular or rectangular pattern that is commonly found in the lineaments that determine fiord and valley directions in districts of crystalline rocks.[22] Far from discovering in this pattern any relation to modern fault dislocation of the surface or even to ancient faults (in areas studied) he finds it present only on "hard rocks with well defined schistosity or cut by angular joints." In Norwegian examples no such pattern is found on adjoining terrains of sedimentary rock. At Hemne Fiord (Norway), which affords an excellent illustration of a rectangular fiord pattern in a gneiss and granite terrain "well marked also in the minor features of the

[21] *Loc. cit.* (20).

[22] O. Holtedahl, On the Geology and Physiography of Some Antarctic and Sub-Antarctic Lands, etc., *Sci. Res. Norweg. Antarctic Exp.*, 3, pp. 128-133, Oslo, 1929.

relief of the surrounding land", Holtedahl finds the two marked lineament directions to correspond with schistosity (striking south-west) and jointing (striking north-west).

Glaciated Pseudo-fiords

While no precise definition of a fiord has been generally accepted, it is usual to exclude from the category of fiords those embayments which though they have been occupied by glacier ice and perhaps owe to it some of their details of form yet have not been excavated in the main by glacial erosion, but preserve to a large extent the contours and profiles of preglacial hollows. A case in point is the Bay of Fundy, claimed as a fiord and attributed to glacial deepening by Shepard[23] but regarded by others as a feature resulting from partial submergence of a valley enclosed between fault-line scarps, being part of a landscape the major forms of which are of preglacial origin.[24]

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[23] F. P. Shepard, Fundian Fault or Fundian Glaciers, *Bull. Geol. Soc. Am.*, 41, pp. 659-674, 1930.

[24] Douglas Johnson, *The New England-Acadian Shoreline*, 1925; E. D. Koons, The Origin of the Bay of Fundy and Associated Submarine Scarps, *Jour. Geomorph.*, 4, pp. 237-249, 1941.

CHAPTER XXI

The Shoulders of Glaciated Troughs

IT IS RARELY that a trough — defined in the sense of the actual channel occupied by the glacier tongue of the last ice flood (Chapter XV) — occupies a whole valley from side to side. "Shoulders" are generally present which distinctly separate steep trough walls from gentler upper valley-side slopes or benches, but signs of overflow of the ice above the shoulders are commonly present.

In addition to those bordering the immediate trough, higher benches are in many cases unmistakably present, though these may be poorly defined owing to partial obliteration by erosion and are always discontinuous, so that their correlation and the restoration of a definite number of actual upper shoulders are by no means certain.

ALPS

Alpine benches in their most perfectly developed form are exemplified by the "alps"—Wengernalp and Grütschalp—on either side of the steep-walled canyon of the Lauterbrunnen trough, in Switzerland, at heights of 2000 feet and more above its floor and separated from it by nearly rectangular shoulders (Fig. 125 and Pl. XLVII, 2). Benches such as these have been interpreted by many observers as remnants of troughs or trough-floors developed in penultimate and earlier glacial epochs, while others see in some of them valley forms made by rivers in interglacial epochs with or without much subsequent glacial modification.[1]

An alternative hypothesis that benched slopes preserve remnants of multicycle preglacial valleys seems to have found no supporters; but a single very remarkable bench in the Otago district of New Zealand must be regarded as entirely preglacial and possibly a river terrace. This is the Crown Terrace, a well-known topographic feature (Fig. 126), which stands as a prominent terrace 600 to 700 feet

[1] E. de Martonne, L'érosion glaciaire et la formation des vallées alpines, *Ann. de Géog.*, 19, pp. 289-317, 20, pp. 1-29, 1910-11.

above the glaciated and drift-covered floor of the Arrow Flat basin. Parts of the terrace itself are veneered with glacial deposits, which indicate that the glacier ice which spread out in the basin was deep enough to overspread the terrace, though only thinly. It can

Fig. 125. The Lauterbrunnen trough (at right) bordered by the Wengernalp and Grütschalp (extreme right) benches.

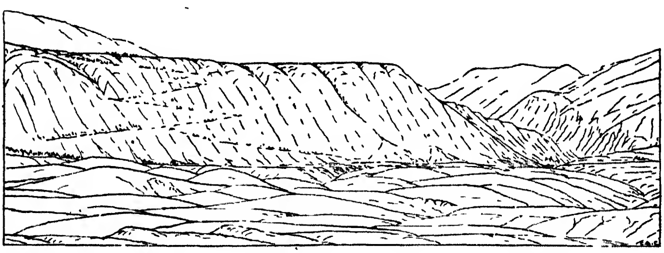

Fig. 126. The Crown Terrace, a very lightly glaciated bench overlooking the Arrow Flat basin, Otago, New Zealand. The basin floor is diversified by drumlinoid ridges and rock drumlins. (From a photograph by Professor James Park.)

have had very little movement or erosive power at that level. Though the Crown Terrace is certainly a preglacial feature of the landscape, the suggestion that it had its origin as a river-cut terrace[2] may be incorrect. Alternatively it may be explained as a tectonic form separated by a preglacial fault scarp from an Arrow Flat "graben".[3]

[2] C. A. Cotton, The Shoulders of Glacial Troughs, *Geol. Mag.*, 78, p. 82, 1941.

[3] So labelled by C. O. Hutton, Metamorphism in the Lake Wakatipu Region, *N.Z. Dep. Sci. & Ind. Res. Geol. Mem.*, 5, Pl. 14 (2), 1940.

Multiple Benches

As regards the *multiple* benched profiles recognised in the valleys of the European Alps, apart from general questions involving divergence of glacial-erosion theories, observers are by no means in complete agreement regarding the interpretation of individual shoulders. Though there can be no doubt of the existence in some parts of some valleys of a stairlike arrangement of valley-side benches (Fig. 127A), many of the attempts that have been

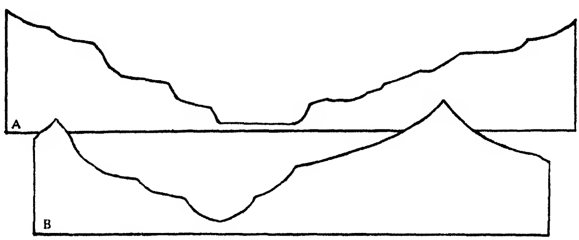

Fig. 127. A: Benches of the Aar valley, near Meiringen. (After de Martonne.) B: Transverse profile of an Alpine valley (Stilluptal) showing an inner trough with side benches and an upper bench formed by cirque-floors. (After Richter.)

made to correlate the benches so as to identify and restore strips of the valley sides of a succession of epochs must be regarded as tentative only. In glaciated regions other than the Alps of Europe traces of benches at various levels are occasionally found, and a general explanation of the origin of such forms is desirable. Successive benches have been noted, for example, even on the steep walls of fiords in south-western New Zealand,[4] though no systematic arrangement of these has as yet been discovered. The benches suggest in places that they are remnants of the walls of compound trough-in-trough valleys (Pl. XLVIII, 1).

Remnants of a Preglacial Landscape

Apart from repeating shoulders of possibly "cyclic" or interglacial origin, the sides of valleys by way of which glacier tongues have made their way out into the zone of ablation bordering glaciated mountains must, it may be deduced, exhibit a trough-

[4] E. C. Andrews, The Ice-flood Hypothesis of the New Zealand Sounds Basins, *Jour. Geol.*, 14, pp. 22-54, 1906.

side shoulder where a lower oversteepened trough side articulates with a non-glaciated upper valley-side slope. The latter may preserve preglacial landscape features with no glacial modification, though wasted away of course to some extent by normal erosion during the Glacial Period. The glaciers may have been thick and heavy enough and maintained sufficient motion to overdeepen the axial parts of the valleys so as to convert them in some cases into the basins which are now piedmont lakes; but, being confined thus to axial positions, they have left the upper slopes unaffected.

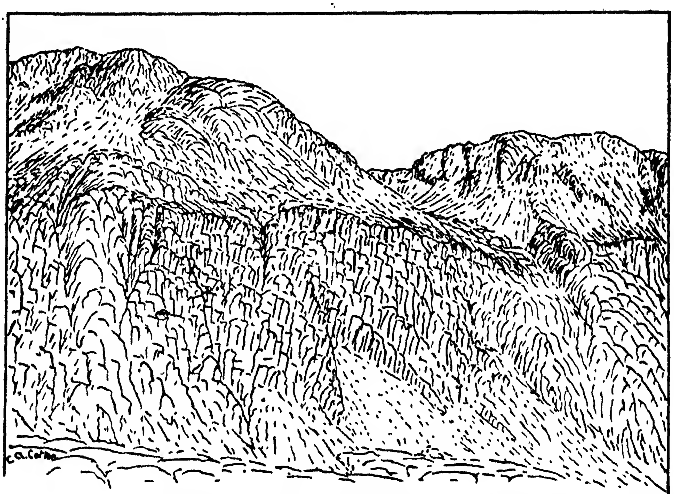

Fig. 128. Shoulder above the eastern trough-wall of the Hooker Glacier, New Zealand. A preglacial surface, somewhat ice-shorn, is present above the shoulder.

Preglacial features, generally less perfectly preserved than those in the marginal or foothills zone, perhaps showing signs of considerable wear by ice during occasional glacial overflows, and cut up to some extent by the development of high-perched cirques, may be present throughout the whole or the greater part of a mountain range (Figs. 128, 129). This hypothesis of the survival of preglacial high-level landscape forms as benches is contrary, however, to the ideas of Sölch,[5] who postulates thorough modification and destruction

[5] J. Sölch, Trogprofile und Trogstufe, *CR. Congr. Internat. Géog.*, 2, pp. 191-197, 1938.

of preglacial relief by intense frost action above the level to which a glacier occupies a valley, the rock material so loosened being effectively removed—and a clean-swept ice-shorn surface left as a high-level, convexly-rounded bench unrelated to the preglacial form—as a result of occasional ice floods.

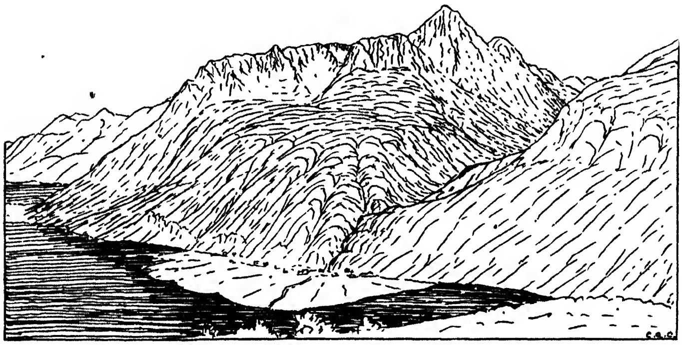

Fig. 129. A bench in which the form of a preglacial landscape seems to survive, overlooking Silvaplana and the Hahnensee, Upper Engadine, Switzerland. (Drawn from a photograph.)

Cirque-floor Benches

In the glacier-head zone of plentiful snowfall among high mountains a bench and shoulder of another kind are commonly present; but regarding the origin of these there can be no question. Here a vigorous and sometimes a very recent development of cirques has taken place at or about a common level determined by a former—and in some cases the present—snow-line, and this has produced continuous benches ("cirque platforms", p. 166) around trough-ends and for some distance down along some valley sides (Figs. 127B, 130), the result being a strongly-marked angular shoulder between the confluent cirque floors and lower slopes which are in some cases oversteepened trough sides. A relation of such benches to present and former snow-lines was pointed out by Richter.[6] According to Taylor the level at which the cirque-cutting process operates to develop such benches is

[6] "*Abtragungsebene der Schneegrenze*" (E. Richter, Geomorphologische Untersuchungen in den Hochalpen, *Pet. Mitt. Ergänz.*, 132, p. 76, 1900).

determined by that of an atmospheric layer with a mean annual temperature of 34°F., and he agrees that the majority of the benches have been cut since the withdrawal of the main ice flood (see p. 182).

In the central parts of the High Alps of Europe either steep trough walls extend to mountain summits and arêtes formed by their intersection, in which case there are no benches of any kind (Pl. XXI, 2), or else there is only the somewhat discontinuous bench made by confluence of the floors of recently developed cirques (Fig. 130). In such cases not only all preglacial forms,

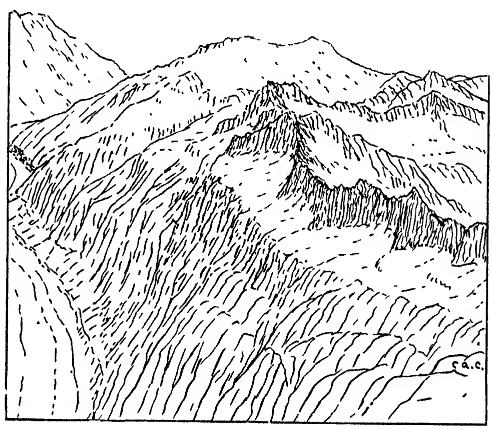

Fig. 130. Bench of recent origin formed by the floors of confluent cirques, arête overlooking the Unteraar glacier, Switzerland. (From a photograph.)

but also all remnants of landscapes developed either in interglacial epochs by normal erosion or in early glacial epochs by glacial erosion have been eliminated by the attainment of landscape maturity in the last glaciation. In some cases of very deep glacial erosion, excavation of the inner trough has also widened it enough even far from valley heads to make the survival of benches impossible. This seems to be the case in the deep glacial canyon of the Yosemite, in California.

Structural Control

The horizontal or gently-inclined arrangement of strata or of nappes is another controlling factor in the development of benches.

In some cases these are very obviously determined by structure, but elsewhere there is an element of doubt and opinions may differ as to whether certain shoulders are "cyclical" or are structurally controlled. Conspicuous benches which are clearly related to outcrops of massive resistant strata may have been developed by selective glacial erosion, but in some cases no doubt they are merely slightly modified structural terraces which date from preglacial or interglacial times (Fig. 131). Benches localised on horizontally-bedded

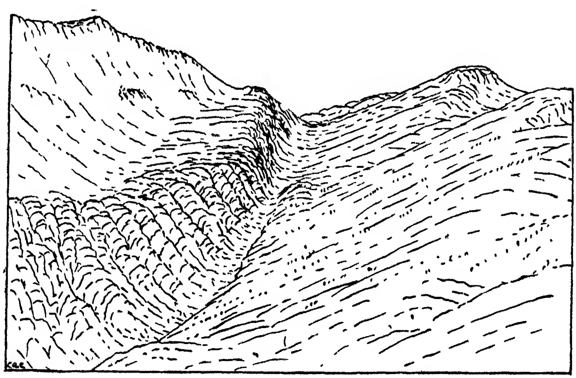

Fig. 131. Structural bench in the homoclinal glacial trough of Upper Slate River valley, Colorado. (From a photograph.)

formations are typical features of the northern Rocky Mountains and of Spitsbergen; and in such regions of intense glaciation the benches cannot be attributed entirely to survival of preglacial forms. "The so-called 'architectural effects' in scenery are commonly associated with beds alternately hard and soft, and either horizontal or dipping but moderately. . . . These conditions are quite as significant in the erosive work of ice as in normal erosion."[7] Structural benches occur in the glacially eroded horizontal lava sheets of north-western Iceland (Pl. XLIX, 1), and also, as shown by Geikie,[8] in the Faroe Islands and in north-west Scotland.

In the limestone Alps of the Bernese Oberland the most frequently cited of all glaciated benches—the "alps" bordering a part of the

[7] N. M. Fenneman, *Physiography of the Western United States*, pp. 206-207, 1931.

[8] J. Geikie, *Earth Sculpture*, 1898.

Lauterbrunnen trough (Pl. XLVII, 2; and Fig. 125)—owe their existence mainly to structure, while above them tower the "architecturally" benched cliffs of the Jungfrau and adjacent peaks (Pl. XLVIII, 2) which resemble those cut out of the horizontal strata of the Canadian Selkirk Range. The exceptionally well-marked Lauterbrunnen benches, though at various altitudes at points not far apart (1277 metres at Wengen and 1642 metres at Mürren), have been regarded by some observers as parts of a preglacial valley floor.[9]

The importance of structural terraces among valley-side bench forms has been insisted on by Blache,[10] who has called attention to the common error of assuming that some of these are instead remnants of valley floors of former landscapes such as may date from preglacial or interglacial cycles of normal erosion or from glacial epochs preceding the last glaciation. The fact that many benches are structural, though obvious, is discounted by some advocates of "cyclical" benches. "The hardness of a rock, it is said, permits the preservation of an erosion-level which would have been destroyed without the support of a solid foundation."[10]

In homoclinal terrains glacially cut structural shoulders may be found on the escarpment sides of valleys (Fig. 131), but in the Otago schist region of New Zealand they are characteristically present only on the dip-slope sides (Pl. XLIX, 2), where they occur somewhat conspicuously as a larger-scale development of the elsewhere small but more numerous glacially excavated terraces previously described (p. 250). Their relation to the dip of the schist foliation is the same—that is, they occur only on trough sides which truncate very obliquely the steeply inclined schist banding.

Lateral Moraine Terraces

An interpretation applicable to some benches, but one which has limited application and is usually easily tested, is that they are lateral-moraine terraces stranded during the shrinkage of the last glaciers or possibly parts of moraine loops related in origin to terminal moraine ridges. Parallel terraces formed of moraines are

[9] W. M. Davis, Glacial Erosion . . . , *Geographical Essays*, p. 650, 1909.

[10] J. Blache, Sur l' interprétation des irrégularités latérales des auges glaciaires, *C.R. Cong. Internat. de Géog.*, 2, pp. 13-22, 1938.

prominent bordering both sides of the broad valley from which the Tasman Glacier (New Zealand) has withdrawn in postglacial time. For some miles there are three of these terrace-forming belts of moraine, all with the same down-valley inclination and separated by vertical intervals of about 1000 feet. One is shown in Fig. 134, p. 317.

Epiglacial Benches

Other benches which are "non-cyclic" and have been formed at quite accidental heights on the sides of some glaciated valleys are those termed "epiglacial" by Blache.[11] These include terraces cut by the lateral erosion of supraglacial water streams originating on large glaciers and also actual gutters developed on valley sides where such melt-water streams have become superposed on them. In the same category may be placed the many features related to ice-margin stream channels which have been described in England and in North America in connection with continental ice-sheet glaciation. "Marginal overflows . . . at first merely shelves cut in the hillside" are described by Kendall,[12] and "in-and-out channels", which make crescentic cuts in hillsides, may also take the form of benches if the channel-cutting process is arrested at an incipient stage. Examples of benches related to ice-margin water channels are found in parts of the "Slaterville channels", in the state of New York, described by Rich.[13] One of these "starts as a slight trimming of the hill slope. This increases gradually until at first a flat bench and later a two-sided channel is cut in the slope." Such forms may be repeated at successive levels, as noted by Kendall,[14] and may produce multiple benching effects.

Cyclic Benches

There are still other multiple benches which cannot be placed in any of the foregoing categories and may have "cyclic" significance. Various theories which have been put forward to explain these are

[11] J. Blache, Le bord d' auge glaciaire de Grésivaudan, rive gauche, *Rec. tr. Inst. Géog. alpine*, 2, pp. 353-417, 1914; A propos des formes glaciaires du Cantal, *Bull. Ass. de Géog. fr.*, pp. 1-3, 1931.

[12] P. F. Kendall, A System of Glacier Lakes in the Cleveland Hills, *Quart. Jour. Geol. Soc.*, 58, pp. 482-3, 1902.

[13] J. L. Rich, Marginal Glacial Drainage Features in the Finger Lakes Region, *Jour. Geol.*, 16, pp. 527-548, 1908.

[14] *Loc. cit.* (12).

of interest as working hypotheses. From the point of view of the explanatory description of landforms the benches present locally fascinating problems whether they do or do not lend themselves to systematic interpretation. Davis, however, has dismissed them as follows:

> Close attention was . . . given in the Aar valley to the occurrence of benches on the valley sides, from which successive epochs of glacial overdeepening have been inferred by some observers. Various opinions were held on this point by different pilgrims. For my own part, while it was easy to recognise one great trough of somewhat irregular or immature form, excavated beneath the higher mountain slopes, and while it was easy to see changes of slope in many profiles of the trough walls, the benches thus indicated were too ill-defined, too irregular, and too discontinuous to be accepted as proving the glacial excavation of a succession of troughs of smaller and smaller size to greater and greater depths.[15]

It is noteworthy that the benches in the valley of the Aar (Haslital) specifically mentioned by Davis are the most strongly marked of several bench flights selected and figured by de Martonne as typical of such forms in the Alpine region (Fig. 127A).

Apart from such interest as they may possess as landscape forms, multiple benched profiles have been appealed to to afford clues to Quaternary history; but the very doubtful nature of conclusions based on such evidence has been pointed out by Blache,[16] who maintains that the only reliable record of a succession of glacial and interglacial epochs is that contained in glacial and fluvioglacial deposits.

It has been recognised that the benches in question are fragmentary and irregular, but a number of patient workers in different Alpine valleys have attempted to arrange them in an orderly sequence. Their correlation from one irregular fragment to another is necessarily tentative and is liable to be influenced by the personal equation, especially where it depends on the interpretation of views from distant vantage points and on the reading of topographic

[15] W. M. Davis, A Geographical Pilgrimage from Ireland to Italy, *Ann. Ass. Am. Geog.*, 2, pp. 73-100, 1912.
[16] *Loc. cit.* (10).

maps, the best of which are liable to be misleading when appealed to on such doubtful questions. Profiles reconstructed from such data, and all of them inevitably influenced to some extent by a prevailing theory, convey the impression of rather well developed, almost terrace-like shoulders, generally four in number, almost continuously bordering some of the main Alpine valleys. Undoubtedly, however, the impression is illusory in some cases at least.[17] Inspection of the photographs chosen, to quote but a single example, by de Martonne[18] from the Rhone valley for a textbook demonstration of the valley-side stairway of benches makes the reader suspect that the benches are in reality so irregular and discontinuous as to defy correlation with any approach to certainty.

Shorn of their quantitative interpretation, on which side one may well maintain an attitude of reserve, hypotheses proposed in explanation of the occurrence of valley-side benches in general must be of considerable value in the interpretation of actual individual bench remnants as landforms. The remnants are regarded with some show of reason as indicators of valley-in-valley arrangement of landscape forms, and attempts are made to restore with their help the longitudinal profiles of valleys that have been successively destroyed prior to and during the excavation of the trough most recently occupied by a glacier in the valley. It is generally assumed most probable that the benches are relics of older glacial troughs, but some restorations of longitudinal profiles which do not reveal any traces of reversed slopes have been regarded as those of rivers, the presence of some reversed slopes having been made a criterion of restored glacial profiles by de Martonne.[19]

Benches Related to Glacial Epochs

The theory of progressive deepening and enlargement of valleys during four successive glacial epochs by glaciers and in the intervening epochs by rivers is rather generally adopted. To account for development of the troughs of which surviving shoulders seem

[17] J. Blache, *loc. cit.* (10), pp. 14-16.

[18] E. de Martonne, *loc. cit.* (1), Pls. 4, 5; *Traité de géographie physique,* 2, Pl. 39, 1935.

[19] E. de Martonne, L'évolution des vallées glaciaires alpines, *Bull. Soc. Géol. Fr.,* 12, pp. 516-547, 1912.

to be remnants the simplest hypothesis is based on that of Richter,[20] who explained the inner trough as having been ploughed out during the last glaciation by a glacier contained within its limits, so that trough-in-trough forms may be tentatively accounted for as the results of excavation by the glaciers of successive epochs. Lack of regularity and continuity of the remnant benches, and in addition the presence on them of abundant traces of recent glaciation in the form of mammillated and polished rock surfaces, fresh morainic deposits, and perched blocks, are among the kinds of evidence that have discredited this hypothesis in the opinion of some observers. It is agreed that most benches were submerged—but for how long there is no means of telling—beneath the ice of the last ice flood, and the older benches have no doubt been thus submerged over and over again. Thus may be explained the discontinuity of benches and their generally damaged condition and palimpsest characteristics. The hypothesis of Richter, however, is not incompatible with the ocurrence of occasional ice floods, the results of which would be some dulling of the edges of otherwise well defined troughs excavated or enlarged during epochs when glaciers were confined to the axial channels. According to Richter[21] typical troughs are developed by "retrogressive" (i.e. lateral) erosion—and where trough edges, or shoulders, are particularly sharp the glaciers which developed the trough features did not overflow their banks. The inner trough shoulder is most strongly marked where, as is a common case in some parts of the world, this trough is so fully developed that it takes up a great part of the valley to the exclusion of any possible remnants of most or all of the hypothetical earlier troughs.

To expect recognition of well and widely preserved records in the form of benches surviving from three glaciations preceding the last, and perhaps also of forms developed in interglacial epochs, demands almost a return to the theory of the non-glacialists that ice is incapable of great erosion or that it produces no forms characteristic of its own work but merely adds in Harker's words, the "final touches" to and shapes the "actual details" of a landscape. Even the initial forms of cirques are astonishingly traced by Fels

[20] *Loc. cit.* (6).
[21] *Loc. cit.* (6), p. 53.

and by Ampferer back to Lower Miocene landscapes.[22] Forms dating from early cycles are regarded as having been mysteriously preserved, however, during the removal of a very considerable thickness of rock material,[23] and the theory of their survival through successive glaciations has something in common with that which assumes the survival (during lateral migration) of slope elements and breaks of slope without change for millions of years in normal landscapes.

When the rapidity with which the side walls of some troughs have been trenched by normal ravines in the short postglacial interval is considered, it does not seem remarkable that the shoulders of the troughs of earlier glaciations have been in reality much dissected and in great part obliterated in long interglacial epochs. Even before their submergence under widespreading later ice floods the shoulders left by early glaciations must already have been reduced to a fragmentary condition by dissection.

Hypothesis of Dominant Vertical Corrasion

As is the case also with the longitudinal profiles (Chapter XIX), the transverse profiles of glaciated valleys are differently explained by the advocates of overdeepening and by those who believe they see traces of more extensive lateral than vertical corrasion. These latter appeal to vertical corrasion by rivers in interglacial epochs for the deepening of valleys throughout the Glacial Period, of which all see evidence. A theory of axial overdeepening, as the process is defined by Penck (Chapters XIII, XIX), accompanied by "oversteepening" of trough walls is relied on by Hess[24] to account for multiple benched profiles.

Lateral strips of broad trough floors developed in early glaciations will be less subject to vertical corrasion than the valley axis (though continuously overspread by ice) in later glaciations, and will thus progressively assume the form of abraded benches. Hess postulates a very broadly open V valley as the initial form at the opening of the first glacial epoch even at a high altitude in the heart of

[22] O. Flückiger, Glaziale Felsformen, *Pet. Mitt. Ergänz.*, 218, p. 48, 1934.

[23] H. Hess, Ueber glaziale Erosion, *C.R. Cong. Internat. Géog.*, 2, pp. 27-37 (gives references to earlier statements of his theory), 1938.

[24] *Loc. cit.* (23).

the Alps, implying far advanced maturity of the whole preglacial landscape. Little modification of valley forms by rivers in interglacial epochs is allowed for, but erosion in the four successive glacial epochs recognised by Penck and Brückner[25] is called upon to do nearly all the work of converting the initially open valley into a trough bordered by benches as it was finally left at the last melting of the ice.

Erosion effected by ice is regarded by Hess as entirely vertical and greatest where the stream is thickest, the latter being an opinion expressed by many glacialists, including Davis.[26] According to Hess's formula the vertical erosive intensity varies as the square of the depth, so that the axis of the valley, where the ice is thickest, is most deepened.[27] In the case of a typical valley selected by Hess as an example he estimates that vertical corrasion has proceeded at rates the average of which is one mm. per year throughout the width of the glacier-eroded valley, but this increases to five mm. per year at the valley axis. The excavation of this valley is estimated to have occupied 600,000 years, but during a considerable part of this it was drained by rivers in interglacial epochs, and to these a very small share of the valley deepening is assigned.

Hypothesis of Dominant Lateral Corrasion

In contrast with the doctrine of overdeepening and oversteepening by vertical corrasion, a theory of dominantly horizontal glacial corrasion is also in favour, having been adopted by Garwood,[28] de Martonne,[29] Sölch,[30] and others, but first stated explicitly by Richter.[31] According to this lateral-corrasion theory valleys are

[25] *Die Alpen im Eiszeitalter,* 1909.

[26] W. M. Davis, *Die erklärende Beschreibung der Landformen,* p. 410, 1912.

[27] It is of interest to compare this argument for vertical corrasion in the valley axis with the opinion of de Martonne, who, though he estimates that erosive intensity varies as the cube of the depth of ice (p. 261), comes to an entirely different conclusion regarding the efficiency of a glacier to corrade vertically and deepen an axial trench in a valley. F. Nansen, it may be noted in passing, regards depth of excavation as related not to thickness or weight of ice but to its velocity alone (Strandflat and Isostasy, *Vidensk. Skr., M.-N. Kl. 1921,* 11, p. 21, 1922).

[28] E. J. Garwood, Features of Alpine Scenery due to Glacial Protection, *Geog. Jour.,* 36, pp. 310-339, 1910.

[29] *Loc. cit.* (1).

[30] J. Sölch, Fluss- und Eiswerk in den Alpen . . . , *Pet. Mitt. Ergänz.,* 219, 220, 1935.

[31] *Loc. cit.* (6), p. 50.

deepened mainly during interglacial epochs, when narrow trenches are cut in their floors by rivers revived (according to de Martonne) by continuous post-Tertiary uplift in the Alpine region. Garwood[32] also has suggested uplift in the last interglacial epoch. Alternation of vertical corrasion, effected by rivers, with glacial corrasion, which is mainly lateral, results ideally in a trough-in-trough valley form, in which the successively opened troughs are, however, of diminishing width and capacity. At the maximum of each later ice flood, therefore, the ice must widely overflow upper benches, and possibly the fragmentation and progressive destruction of these may thus be satisfactorily accounted for.

According, however, to a formula given by de Martonne[33] for the friction between the glacier and its bed, which is relied on by him as determining the measure of vertical corrasion, the friction varies as the cube of the thickness of the ice, and the enlargement of V-shaped valleys by widening into trough forms apparently by a concentration of vertical corrasion at the thin margins of ice streams seems inconsistent with the formula. De Martonne relies on this formula only for the explanation of the development of typical longitudinal glacial-floor profiles, but explains the cross profile of the trough as solely due to the efforts of the ice stream to cut for itself a channel bounded below by an arc of a circle —the "hemicylindrical groove" of Richter.[34]

Though it is termed *"sapement"* by de Martonne and referred to as "retrogressive" erosion by Richter and Sölch, the kind of erosion which is relied on by these authors for transformation of valley profiles from V to U form is purely vertical corrasion by the ice stream, such as may be regarded as analogous with the action of a straight stream of water deepening a gorge. Only occasionally references have been made to the possibility of lateral corrasion taking place that is in any way analogous with the familiar undercutting by water streams on the outer sides of curves—e.g. by

[32] E. J. Garwood, On the Origin of Some Hanging Valleys in the Alps and Himalayas, *Quart. Jour. Geol. Soc.,* 58, pp. 703-718, (1902); *loc. cit.* (1910).

[33] E. de Martonne, Quelques données nouvelles sur la jeunesse du relief préglaciaire dans les Alpes, *Rec. de trav. Cvijic,* p 136, 1924.

[34] *Loc. cit.* (6), p. 50.

Andrews[35] and by von Engeln[36]—but scored and polished vertical fiord-walls and trough-side cliffs (Pl. XLII, 2) indicate that steepening by undercutting does take place. Very rarely also has true lateral sapping by freeze and thaw along the sides of glaciers been considered as a possibility. This is a process that may perhaps result in valley-side steepening after the manner of head-wall recession in cirques. Gilbert[37] has found trough sides thus steepened by sapping near valley heads in the Californian High Sierra, and Taylor[38] has developed in detail a hypothesis to account for shaping by frost work of broadly U-shaped or catenary trough forms with or without some help from glacial corrasion (Chapter XVI).

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[35] E. C. Andrews, *loc. cit.* (4).

[36] O. D. von Engeln, Glacial Morphology and Glacial Motion, *Am. Jour. Sci.*, 35, p. 439, 1938.

[37] G. K. Gilbert, Systematic Asymmetry of Crest Lines in the High Sierra of California, *Jour. Geol.*, 12, p. 582, 1904.

[38] G. Taylor, Physiography and Glacial Geology of East Antarctica, *Geog. Jour.*, 44, pp. 365-82, 452-67, 553-71, 1914; *The Physiography of the McMurdo Sound and Granite Harbour Region*, London: 1928.

CHAPTER XXII

The Doctrine of Glacial Protection

INVESTIGATION of such landscape features as cirques, rock basins, valley-head stairways, hanging valleys, piedmont lakes, and fiords, all of which are found in association with obvious signs of the former presence of glaciers, has frequently raised the question of the nature of the relationship between such forms and the glaciers, and on this subject strongly divergent opinions have been held by geomorphologists. Davis[1] has not hesitated to brand the peculiar landforms characteristic of glaciated mountains as "abnormal" as compared with the "normal" features found among mountains that have never nourished glaciers in their valley-heads; and explanations of such features as in some way or other the products of glacial erosion now meet with general acceptance. Most hypotheses of glacial erosion have, however, been at some time vigorously opposed, and some of the arguments used against them must still be mentioned in any full discussion of glaciation.

MULTIPLE WORKING HYPOTHESES

Among possible methods of discussion of glacial erosion suggested by Davis[2] is a "search for other explanations of features that are ascribed to glacial erosion"; and among additional explanations which should be critically examined are: "Warping of normal valleys to produce lakes; faulting to produce hanging lateral valleys; revival of normal erosion by tilting to produce hanging valleys . . . ; subglacial stream erosion, or ordinary stream erosion during interglacial periods, to produce overdeepened valleys; and so on." Obviously all these processes are capable in special circumstances of producing forms resembling *in some respects* the landscape forms characteristic of glaciated mountains. Any geomorphologist now investigating mountain landscapes keeps such hypothetical explanations in mind: he goes farther than that and deduces their collateral

[1] W. M. Davis, Glacial Erosion in North Wales, *Quart. Jour. Geol. Soc.*, 65, p. 304, 1909.

[2] *Loc. cit.* (1), p. 306.

consequences, for traces of which he seeks in the field as tests of the hypotheses. The alternative explanation of piedmont Alpine lakes by warping, which had been widely accepted among opponents of glacial-erosion theories, was, for example, quite definitely shown by Wallace to be inadmissible because of the absence of the many branching embayments which lakes formed by warping of normal valley systems must have (Chapter XX).

Glacial Protection

Chief among the alternative hypotheses of more than local application that have been proposed in explanation of the various "abnormal" glacial features is the theory of "glacial protection," which had at one time many adherents and was strenuously advocated by some geologists of the highest standing, especially in Britain. The doctrine of protection is not essentially a denial that glaciers act as eroding agents, but its main tenet is that they are relatively feeble and slow eroding agents liable to be outpaced both by the contemporary wearing and wasting away of mountain summits subject to weathering and by the incision and widening of valleys subject to river erosion. Thus, Freshfield, an avowed protectionist, has said: "Our school is misrepresented when it is asserted that we deny any destructive action by ice. We hold that the question is one of *relative* power."[3]

The logical outcome of a doctrine of relative weakness and slow tempo of glacial erosion (except in cases where subglacial rivers have been assumed to be responsible for extensive erosion) is that not only snowfields and stagnant ice masses such as "ice slabs" or dead glaciers but also rapidly moving ice streams must act as protectors of the surfaces on which they lie and over which they flow, while other parts of a landscape not thus protected continue to be worn down and dissected by normal weathering and stream work; and so selective protection of the land surface has been appealed to for an explanation of those features of glaciated landscapes more generally regarded as the peculiar consequences of vigorous glacial erosion.

A school of prominent Alpinists and geomorphologists in the nineteenth century consistently refused to regard the special features

[3] Douglas Freshfield, *Geog. Jour.*, 36, p. 338, 1910.

of glaciated valleys as "abnormal" in the sense of being different from those which they expected to find in landscapes sculptured without glacial complications by rivers in preglacial and interglacial times. The invasion and occupation of the valleys of such landscapes by ice had resulted, they believed, in few changes; and from this conclusion they derived their two main tenets, first, that glaciers are feeble eroding agents and, secondly, that ice is protective. Thus most of the opponents of theories of glacial erosion have gone farther and proclaimed themselves protectionists.

One of the earliest declarations in favour of the protection theory was made by Rütimeyer,[4] who described glacial periods as "pupa stages" in valley development and said: "The work of valley formation, which slumbered under the glacier, only awakens when the glacier leaves them." Whymper[5] pronounced glaciers "conservative" rather than "destructive." Albert Heim[6] ascribed very little erosive ability to ice, and said: "Glaciation is equivalent to relative cessation of valley formation." He found in the protection theory an explanation even of the great depths of fiords as compared with nearby off-shore depths, ascribing them to occupation (not erosion) of the fiord valleys by ice, which preserved the (unexplained) great preglacial depth by preventing accumulation of rock debris.[7] Another early advocate of glacial protection was Freshfield.[8] Protection theories have been most strongly advocated as competitors of the doctrine of glacial erosion by Bonney,[9] Garwood,[10] and Kilian.[11]

[4] L. Rütimeyer, *Ueber Tal- und Seebildung,* 1869.

[5] E. Whymper, *Scrambles Among the Alps in the Years 1860-69,* 1871.

[6] A. Heim, *Handbuch der Gletscherkunde,* p. 401, 1885.

[7] A. Heim in R. von Lendenfeld, *Australische Reise,* pp. 178-180, 1892.

[8] D. W. Freshfield, Note on the Conservative Action of Glaciers, *Proc. Roy. Geog. Soc.,* 10, pp. 785-787, 1888.

[9] T. G. Bonney, Lakes of the North-eastern Alps and their Bearing on the Glacier-erosion Theory, *Quart. Jour. Geol. Soc.,* 29, pp. 382-395, 1873; Do Glaciers Excavate?, *Geog. Jour.,* 1, pp. 481-499, 1893; *Ice Work Past and Present,* 1896; Alpine Valleys in Relation to Glaciers, *Quart. Jour. Geol. Soc.,* 58, pp. 690-702, 1902; Presidential Address, *Rep. Brit. Ass. Sheffield,* pp. 3-34, 1910; *The Work of Rain and Rivers,* pp. 32-38, Cambridge, 1912.

[10] E. J. Garwood, On the Origin of some Hanging Valleys in the Alps and Himalayas, *Quart. Jour. Geol. Soc.,* pp. 703-718, 1902; Features of Alpine Scenery due to Glacial Protection, *Geog. Jour.,* 36, pp. 310-339, 1910; Presidential Address, *Quart. Jour. Geol. Soc.,* 88, pp. xciii-cxviii, 1932.

[11] W. Kilian, Note sur le "surcreusement" ("Uebertiefung") des vallées alpines, *Bull. Soc. Géol. Fr.,* (3) 28, pp. 1003-1005, 1900; L'érosion glaciaire et la formation des terrasses, *La Géographie,* 14, pp. 261-274, 1906.

Commonly associated with the application of protection theories is an ancillary hypothesis, advocated especially by Freshfield[12] and Brunhes,[13] but rejected for good reasons by glacial erosionists,[14] that much erosive work has been done by rivers of melt-water running under glaciers (p. 140).

Hanging Valleys

It is one of the best supported beliefs of glacial erosionists that the presence of hanging valleys bordering a glaciated valley is to be attributed to enlargement of the valley (by overdeepening or otherwise) as a result of glacial erosion; and it is of interest to examine Garwood's[15] alternative theory of their origin, applied to the Ticino valley in particular, which involves application of the hypothesis of glacial protection. The line of argument is as follows: Ice is a less efficient eroding agent than water; and therefore the inner trough of the valley must have been excavated by river erosion; but this capacious, broad-floored valley is bordered by hanging side-valleys, the non-incision of which during the excavation of the main trough must be explained as a consequence of their occupation and *protection* by glaciers. Thus originates the theory that glaciers have survived in side valleys and protected them from erosion during an interglacial epoch, when the main valley has been ice-free and subject to river erosion. (Bordering some fiords from which glaciers have retreated in Spitsbergen glaciers do linger in side valleys; but it must be noted that the reverse is the case along the sides of axial valleys in mountain regions which are still occupied by active glacier tongues thrusting far down into the zone of ablation.)

The main Ticino valley (Valle Leventina), the form of which has been taken by Davis and others to be typical of a trough over-deepened by glacial erosion, has been described by Garwood as a normal river-eroded valley with interlocking valley-side spurs, but

12 D. W. Freshfield, *loc. cit.* (8).

13 J. Brunhes, Erosion fluviale et érosion glaciaire, *Rev. de Géog. Ann.*, 1, pp. 281-308, 1906-7.

14 See, for example, W. M. Davis, *Die erklärende Beschreibung der Landformen*, pp. 411, 417, 1912.

15 As expounded in 1902 (*loc. cit.* (10)).

a large-scale contoured map accompanying the description fails to substantiate these features above the level of the shoulders of postglacial river-cut gorges through riegels. Moreover, the valley-floor is diversified by riegels separating open-floored basins (Fig. 116). Gorges through the riegels, which are obviously river-cut, are to other eyes postglacial, but must be regarded by a "protectionist," in accordance with the view that the whole trough is to be interpreted as of preglacial origin, as connecting links between graded reaches developed by a river before the last glacial epoch.[16]

It is only fair to Garwood to mention that he later[17] modified his theory of glacial protection, abandoned the extreme position taken up in 1902, and attributed a considerable share of the shaping of glacial troughs to glacial erosion. It is true, indeed, that since the first decade of the twentieth century there has been convergence between the views of glacial erosionists and their opponents. The doctrine of the glacial erosionist de Martonne[18] (foreshadowed by Richter and Frech) that glaciers work laterally rather than vertically in the enlargement of troughs, and that these owe their deepening mainly to river erosion in interglacial epochs, was adopted almost simultaneously by Garwood, an avowed protectionist, and fusion of the two schools of thought is found in the composite hypothesis of Sölch.[19]

Cirques

In explanation of the origin of cirques the theory of glacial protection has been invoked by Garwood and earlier by Bonney, whose indictments of what he considered the extravagant claims of glacial erosionists are sometimes couched in very vigorous terms. Cirques still occupied by hanging glaciers and those not now containing glaciers but affording clear evidence of having done so in the past were regarded by Bonney as the "cause," not the "consequence" of the glaciers.[20] Their form he explains as a result of the

[16] This point of view and also the suggestion that the gorges have been cut by subglacial streams of melt-water have been already referred to in Chapter XIX.

[17] *Loc. cit.* (10), 1910.

[18] E. de Martonne, L'érosion glaciaire et la formation des vallées alpines, *Ann. de Géog.*, 19, pp. 289-317 (1910); 20, pp. 1-29 (1911).

[19] J. Sölch, Fluss- und Eiswerk in den Alpen zwischen Ötztal und St. Gotthard, *Pet. Mitt. Ergänz.*, 219, 220, 1935.

[20] *Loc. cit.* (9), 1902, p. 692.

action of convergent headwater tributaries in a normal valley or ravine head, but the examples of stream work he cited as affording illustrations of the process in operation were all drawn from terrains of horizontally bedded and nappe structures, and indeed he specified a necessity for such structure in cirque development, namely:

> strata, moderately horizontal, over which these streams fall, and which by their constitution yield considerably to the other forms of meteoric denudation; these strata must nevertheless allow of the formation of cliffs, and thus perhaps the most favourable structure is thick beds of limestone with occasional alternating bands of softer rock.[21]

Such a structure does certainly favour the development of amphitheatre-headed normally-eroded valleys, [21a] the upper parts of which may be perched on structural shelves like those bordering the Grand Canyon of the Colorado; but this very special type of terrain is of course by no means coextensive with the distribution of cirques of ideal form either in the European Alps or any other part of the world. The processes invoked would not, moreover, afford any clue to the origin of the rock-rimmed lakes present on the floors of many cirques, even if all cirque-like features occurred in horizontally bedded terrains.

Some support has been given to Bonney's theory of structural control of cirques by McCabe,[22] who has given close attention to corries now developing on horizontal rock outcrops in Spitsbergen. His findings have obviously no application to other terrains, however.

Bonney was an antiglacialist rather than a glacial protectionist, but he ranged himself with the latter school when he expressed the opinions "that the action of permanent snow is more conservative than destructive" and "that the erosive effect of a glacier is at a minimum beneath a comparatively level névé such as is often found at the base of a rock wall not seldom from 300 to 600 or 700 feet high"[23] [that is, in a cirque].

[21] *Loc. cit.* (9), 1912, p. 38.
[21a] Compare N. E. A. Hinds, Amphitheatre Valley Heads, *Jour. Geol.*, 33, pp. 816-818, 1925.
[22] L. H. McCabe, Nivation and Corrie Erosion in West Spitsbergen, *Geog. Jour.*, 94, pp. 447-465, 1939.
[23] T. G. Bonney, *loc. cit.* (9), 1902, p. 699.

The specific application of the protection theory to cirque development was left to Garwood,[24] who by this time, however, had become to some extent an advocate of glacial erosion. He says: "Their origin is ascribed by many writers at the present day to ice erosion, and no doubt the special armchair form and smoothed, glaciated surfaces are directly due to this cause." Also "the corrie wall behind has been riven by frost and has gradually retreated backwards." Cirques are described, however, as features of high trough-side benches, being "the modified heads of old lateral tributaries draining the sides of an old valley situated at a much higher level than the present one," and the theory is advanced that cirque glaciers have been protective in that their presence has delayed the destruction by normal erosion of the benches on which they rest and of which the cirques form a part.

Valley-floor Steps

As protagonist of the glacial protection theory Garwood has invoked it to explain also the steps in longitudinal profiles of glaciated valleys, dismissing all other proffered explanations as inadequate. Garwood's theory[25] was proposed very shortly after, and was perhaps influenced by, Davis's[26] closely reasoned discussion of a similar hypothesis, which had never before that been fully stated or discussed.

In brief, Garwood assumes the development of typically three steps in each glaciated valley, corresponding to three epochs of fluvial valley-deepening during three interglacial epochs. The glacier is assumed to shrink, and its terminal face to retreat up-valley, but not to disappear from the landscape, during each mild epoch, retreating farthest in the first, less far in the second, and least in the third interglacial epoch, to advance to its maximum during the last glaciation, and in the postglacial interval either to disappear or to shrink to minimum dimensions. (It is difficult to reconcile the "interglacial" survival of the glaciers and the extensive postglacial shrinkage with the graph of Quaternary temperatures given by Hess, which Garwood has accepted. The limited amount of inter-

[24] E. J. Garwood, *loc. cit.* (10), 1910.
[25] *Loc. cit.* (10), 1910.
[26] W. M. Davis, *loc. cit.* (1).

glacial retreat is explained as depending on the duration of the mild epochs. Thus the limited extent of retreats allowed for suggests that interglacial epochs were very short, which is inconsistent with the amount of normal erosion ascribed to them as well as with other evidence. As the temperatures assumed for the interglacial epochs are considerably higher than that of the present day the epochs can be each allowed a length which is only a fraction of the short post-glacial interval, for otherwise the complete withdrawal of the glacier in postglacial time is an unexplained mystery.) The last interglacial retreat was accompanied by uplift of the land, sufficient to revive fluvial erosion, and the reader may infer similar conditions in the earlier interglacial epochs.

The glacier is assumed to be an efficient protector of the landscape against vertical erosion, though credited with an ability to enlarge a valley laterally, and so protects the rock floor beneath it from incision; but in each of the three interglacial epochs (though not to any great extent in the postglacial interval) rivers have cut trenches in the exposed parts of the valleys, the very steep heads of these trenches have been pushed close up to the ice front, and the valleys thus deepened have been enlarged by the glaciers during each of the three later glacial epochs, when they have converted "the V-shaped into a U-shaped valley with steep sides." A step at the head of each such down-valley trough has been protected from vertical erosion owing to its being covered by the glacier, and has been subject only to smoothing and rounding of its edges (after the down-valley trough has been enlarged by glacial erosion to the extent of fully developing the step). Only after the final retreat of the ice has the step been exposed to weathering and fluvial erosion.

This scheme has little flexibility in that it requires the presence of three steps in every glaciated valley (unless one or more still remain covered by a lingering glacier) and is in many respects at variance with well established principles of geomorphology which had already been applied by Davis in his analysis of the consequences of the protection theory. Apart from these defects, however, the theory is unacceptable because of the impossibility of reconciling the concept of only a limited amount of glacial retreat with the accepted doctrines of long duration and high temperatures of interglacial epochs.

Davis on Glacial Protection

With full consideration of all its consequences the protection theory has been stated by Davis[27] in the capacity of devil's advocate. He assumes that a wholehearted protectionist will require the valleys below steps resulting from glacial protection to be not only deepened by river erosion but widened also by the same process. It is postulated that steps may be thus developed during halts either in an advance or retreat of glaciers; but steps cut during a protracted and interrupted retreat will be destroyed progressively by river erosion. This explains the conclusion of Garwood (as stated above) that the step farthest up a valley is the most ancient and that the whole system of steps records oscillations of the ice front the algebraic sum of which has been a progressive advance culminating in the last glaciation.

The most illuminating of the numerous drawings made by Davis in illustration of his analysis of the consequences of glacial protection is that one which places side by side diagrams showing in the one case stepped valleys and surrounding landscape forms which are deduced consequences of the protection theory and in the other the features of a landscape deduced from the hypothesis that glacial erosive processes are vigorous and efficient.[28] The latter diagram, it may be noted, does not show steps on the main valley floor, but this omission need not be taken as an assertion that glacial erosion is incapable of developing a stepped profile in such a valley. At points of glacial confluence and possibly also at places where the main valley is crossed by belts of resistant rocks, steps and perhaps riegels might well have been introduced; but the chief value of the diagram lies in its portrayal of the contrast between forms of side valleys and valley heads, and also of crest-lines, deduced from the two contrasted hypotheses. In these diagrams redrawn and reproduced as Fig. 132 some steps are introduced.

Among the objections to the glacial protection theory which arise out of Davis's discussion of the hypothesis a selected few are as follows:

No entrenchment of valleys can take place downstream from a stationary glacier terminus unless as a result of uplift, and if this

[27] W. M. Davis, *loc. cit.* (1).
[28] *Loc. cit.* (1), Figs. 20, 21.

is discontinuous each spasm of uplift must be synchronous with the establishment of a new position of the ice front. "The necessary postulate of increasing uplift with increasing glaciation [however] runs counter to the evidence which in many regions associates increasing glaciation with depression."

As regards the number of steps, this "should correspond in each of the several radiating valleys of a mountain group like Snowdon; for each step is only the local result of a well-maintained climatic

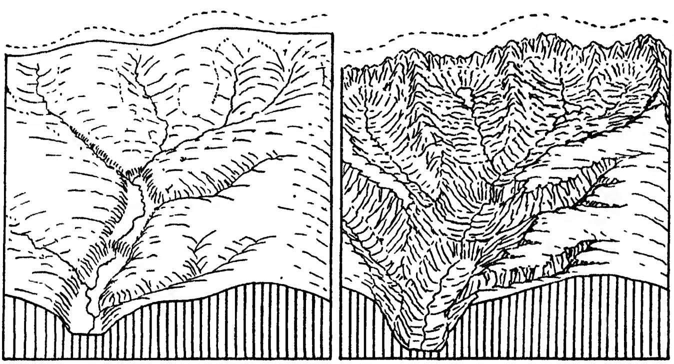

Fig. 132. Diagrams contrasting the consequences of the erosion of a landscape of initially subdued mountain forms on the hypotheses of glacial protection (left) and glacial erosion (right). Dotted lines indicate the boundaries of the areas that have been covered by glaciers. (After Davis, redrawn with slight alteration.)

episode which must have been of essentially uniform value all around the mountain group. Furthermore, the height and spacing of the corresponding steps should be systematically related, for each set of steps is the result of a single climatic change and of a single uplift."

Hanging side valleys also should occur in sets, those in each set irrespective of their size being accordant in altitude, and each such set of side valleys should be accordant with the tread of the next up-valley step.[29]

Perhaps the best argument against the protection theory of steps is, as already stated, afforded by a glance at Davis's diagrams

[29] W. M. Davis, *loc. cit.* (1), pp. 311-312.

showing the deduced consequences of the hypothesis as regards the development of the landscape as a whole.

Restricted Application of the Protection Hypothesis

Though it has proved inadequate as an explanation of landscape forms which more surely have resulted from glacial erosion, the hypothesis of glacial protection need not be rejected entirely. Thick and rapidly flowing ice streams are undoubtedly vigorous eroding agents, but, on the other hand, sedentary snowfields and thin and stagnant ice caps and dead glaciers cannot fail to protect the rock surfaces beneath them to some extent from frost action and almost entirely from river erosion. Such protection seems to have been afforded for a very long time to plateaux in arid Antarctica,[80] and Garwood's[81] observation that the mouths of Alpine hanging valleys facing south and west are more deeply trenched by river-cut ravines than those facing north and east may perhaps be correctly interpreted as a result of the protection afforded to the latter by sluggish remnants of glaciers which have lingered in them at the close of the last glacial epoch. It has been said that even thick sheets of moving ice may have effectively protected hard-rock surfaces beneath them after the products of preglacial weathering have been swept away, as the ice has thereafter been unable to provide itself with sufficient rock debris to be of use as abrasive material.[82] "After removal of the loose material, [however,] there should be some continuance of erosion by plucking from the sharper edges of the major topographic forms. Yet in time even these should be rounded off, and an end stage of erosion should be reached. After this the ice could exert a protective influence only."[83] Thus modified the newer doctrine of protection implies protection not of the preglacial but of a glacially eroded surface. It is an argument for a *gradual* slowing down until "if a comparison of erosional rates should show, as it might,

[80] Griffith Taylor, Physiography and Glacial Geology of East Antarctica, *Geog. Jour.*, 44, pp. 365-382, 452-467, 553-571, 1914. Similar protection of the plateau of North-east Land (Spitsbergen) has recently been described by A. R. Glen, A Sub-Arctic Glacier Cap: the West Ice of North-east Land, *Geog. Jour.*, 98, p. 76, 1941.

[81] E. J. Garwood, *loc. cit.* (10), 1902, p. 709.

[82] M. Demorest, Glaciation of the Upper Nugssuak Peninsula, W. Greenland, *Zeits. f. Gletscherk.*, 25, pp. 36-56, 1937.

[83] M. Demorest, Glacial Movement and Erosion: A Criticism, *Am. Jour. Sci.*, 237, p. 603, 1939.

that a continental glacier during the plucking stage erodes less rapidly than subaerial processes, one can believe that ice in this stage is relatively more protective than destructive of the land."[34]

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[34] M. Demorest, *loc. cit.* (82), p. 47. Working in another part of Greenland N. E. Odell has reached conclusions very similar to those of Demorest (The Glaciers and Morphology of the Franz Josef Fjord Region, North-east Greenland, *Geog. Jour.*, 90, pp. 111-125, 233-258, 1937).

CHAPTER XXIII

Morainic Constructional Forms

THE ICE OF most present-day valley glaciers is encumbered with an enormous load of rock debris which must be disposed of as the ice melts at the terminal face and throughout a broad zone of wastage behind it. In this zone extensive surface moraines are re-emerging as a result of ablation after long burial beneath snow and avalanche ice, and such rock debris may be so abundant as completely to hide the glacier ice (Pl. XVIII, 2). The deeper ice also contains, and is in some cases packed quite full of, englacial debris (Pl. XVII), and subglacial debris is dragged along beneath the sole of the glacier. Glaciers of the Ice Age carried loads that were similar in a general way, and the same is true of continental ice sheets both of the present and of the past.

The proportions of coarse and fine debris and of angular and rounded fragments vary, and have varied, very widely, however, depending obviously upon the relief and extent of the rock slopes and peaks (if any) shedding frost-riven debris on to the glaciers —depending also on the nature of the rocks, hard or soft, that are undergoing denudation, on the precipitation, which governs the volume and velocity of off-flowing ice, and, no doubt, on various other factors.

MORAINIC DEBRIS

On the present-day glaciers of New Zealand, surrounded in the zone of alimentation by rocky peaks and slopes, and especially on those glaciers east of the main divide, where the outcropping rocks undergo mechanical disintegration at a conspicuously rapid rate, morainic loads seem to consist exclusively of coarse angular material. There is commonly, on the other hand, in the loads carried by many glaciers a substantial proportion of fragments that have been well rubbed down and even thoroughly rounded by glacial abrasion; and the debris carried by glaciers and ice sheets of the Glacial Period, especially in regions where few or no unsubmerged peaks

(nunataks) were present to shed fragments on to the ice surface, included a very large proportion of sand, silt, and even clay, though generally with a sprinkling of boulders and much well-worn gravel.

In districts where the average grade of debris is fine occasional bouldery accumulations of glacial origin are termed "bear-den" moraines. The boulders composing them have been selected from the bulk of finer material by some rough sorting process, such as by rolling down an ice slope. In other cases, perhaps, fine material originally deposited with the boulders has afterwards been washed away.

Rock fragments and boulders that merely ride upon a glacier are subject to no mechanical wear, and even englacial debris is little worn except at and near the bottom of the ice stream. Ablation moraine may contain smoothed and rounded blocks, however, near the terminal face of a glacier if such debris has been brought up from lower layers by differential flow of the ice stream.

Surface blocks if they lie long enough exposed to the atmosphere on a sluggish or stagnant glacier crumble away and are reduced to heaps of angular debris—the "debris cones" on Antarctic glaciers.

Abrasion of Glacial Debris

A considerable proportion of the blocks in the glacial debris of mixed character carried by continental glaciers, and even by some valley glaciers, have their angles rubbed off, and pebbles are quite commonly smoothed and show evidence of much wear, though all the blocks and smaller fragments may have been plucked from bedrock or otherwise picked up by the glacier in an unworn, angular condition.

Many of these, especially those transported in the deeper part of the ice stream, seem to have been "subjected to almost continuous rotation in a scouring medium. Under these circumstances a non-faceted, rounded, elliptical, cylindrical, in general ovoid pebble is produced. It may be abundantly striated in generally criss-cross pattern."[1] A gravel composed of such pebbles would be scarcely distinguishable from river gravel were it not for the fact that

[1] O. D. von Engeln, Type Form of Faceted and Striated Glacial Pebbles, *Am. Jour. Sci.*, 19, pp. 9-16, 1930.

the pebbles are mixed with sand and clay and occasional boulders and are themselves of mixed sizes. Furthermore, there are present odd pebbles, a varying proportion of the whole, which are more characteristically of glacial origin in that they are coarsely striated, faceted, and even "soled"—that is, have a large flat surface developed on one side owing to their "having been held against an unyielding surface (the bedrock over which the ice was moving) in one position for a considerable distance" (von Engeln). The abrading material

Fig. 133. Glacially faceted and scratched limestone pebble. (After Chamberlin.)

actually responsible for most of the rubbing down both of the pebble and of the rock surface beneath it, which is polished and scratched in a similar way (Chapter XVIII), must have been the gritty particles caught between rock fragments and bedrock.[2] Such particles are soon pulverised to form the characteristic rock flour carried by glacial melt-water, but a plentiful supply of fresh sand grains and small rock fragments is generally available.

Among "soled" pebbles and boulders the "flat-iron" shape (Fig. 133) or some approach to it has been found to be most common. Many other facets besides the pronounced and characteristic sole

[2] T. C. Chamberlin, The Rock-Scorings of the Great Ice Invasions, *U.S. Geol. Surv. Ann. Rep.*, 7, p. 234, 1888.

may be developed, perhaps as the pebble rolls along but is occasionally gripped by the ice, a process described by Chamberlin[3] as "a literal illustration of playing fast and loose". Von Engeln, on the other hand, holds that the minor facets which trim a "flat-iron" pebble or boulder into shape are developed concurrently with the rubbing-down of the sole. "The friction due to contact with the bedrock would cause the fragment to lag behind the general motion. Hence the debris-laden bottom ice tended to flow over [it]. . . . Thus the lateral facets striated downward toward the prow would be developed but not so perfectly as the basal sole. . . . The broad back which takes the thrust . . . is comparatively little affected by the striating process."[4] Even large boulders may assume the flat-iron shape (Pl. L, 2).

Glacial Deposits

Nearly all the deposits which make conspicuous landforms and are composed of glacially-transported debris have been laid down under, at, or near either the snout of a valley glacier or the margin of an ice sheet—in the zone of ablation, that is to say, where debris is released in quantity from the ice.

Nearer the sources and especially under the thick middle sections of valley glaciers, and not far from the high-piled centres of continental glaciers, erosion has been active, and rock surfaces have been first stripped of all loose (preglacially weathered) debris, then abraded, scored, and even polished (Chapter XVIII). It must be remembered, however, that during the waning of glaciers and ice sheets the termini and ice margins have generally withdrawn, and so the zone of deposition has been extended towards the source. Some deposits of glacial debris are found resting, therefore, on well-worn glaciated land surfaces, more especially in the lee of surviving rocky knobs. Rapid wastage of ice that has ceased to flow has also resulted in deposition of all the debris it has contained.

Ground Moraine

Discontinuously or continuously, here thin there thick, a layer of glacial debris has been spread very widely over the regions

[3] *Loc. cit.* (2), p. 209.
[4] *Loc. cit.* (1), p. 14.

that have been covered by continental glaciers. Hills and valleys alike have been coated with it, in some cases so evenly as scarcely to modify the form of the underlying bedrock surface. Commonly this "ground moraine" layer still remains with a smooth surface as it has come to rest, but in some places it is eroded and dissected. The material, termed "till" or "boulder clay", consists of more or less plentiful clay or silt with sand, pebbles, and boulders scattered through it (Pl. LI, 1 and 2). Its mode of deposit precludes any stratification or sorting of the various grades of debris from one another into discrete strata. In North America a widespread layer of compact ground moraine, in places very thick, appears to be a subglacial deposit, overridden and compressed by the ice sheet, while above this may lie less compact till let down when the last of the ice melted away.

Perched Blocks

Where the layer of glacially deposited debris thins out and exposes the abraded bedrock surface, some scattered and "perched" blocks remain. Such relics of the Ice Age, some of which rest on hilltops, were among the first evidences of glaciation to attract attention. Some are "erratics"—far travelled from their parent rock-outcrops and recognisably of rock types different from those of their present surroundings (Pl. L, 1).

Morainic Relief

All locally heaped accumulations of unsorted glacial debris are referred to as "moraines". The piles of morainic debris are generally more or less elongated parallel to the ice margin. Some are hummocky ("knob-and-kettle" moraines) (Pl. LII, 1 and 2), some smooth and flattish, while others assume definite ridge forms. Smooth-surfaced moraines have perhaps been overridden by ice during a re-advance of the ice front, so as to eliminate hummocks on the original depositional form.

Stranded Moraines

The regular ridges carried on valley glaciers as lateral moraines and built of fallen angular blocks of every size are deposited in some cases bodily during rapid shrinkage of the ice stream. If they

preserve the ridge form they are still called "lateral moraines." Stranding of the ridges on valley-sides can occur only where the glacier-containing troughs have a broadly open catenary form (Fig. 134) or where there is at least locally a level enough lodgment—such as is afforded by the presence of a bench of structural or other origin—for the stranded moraine to rest upon. There are some excellent examples in New Zealand of stranded moraine ridges parallel to and in every way similar to the lateral moraines that rest on the actively moving (though now shrunken) glaciers still occupying the valleys below them (Pl. LIII, 1 and 2).

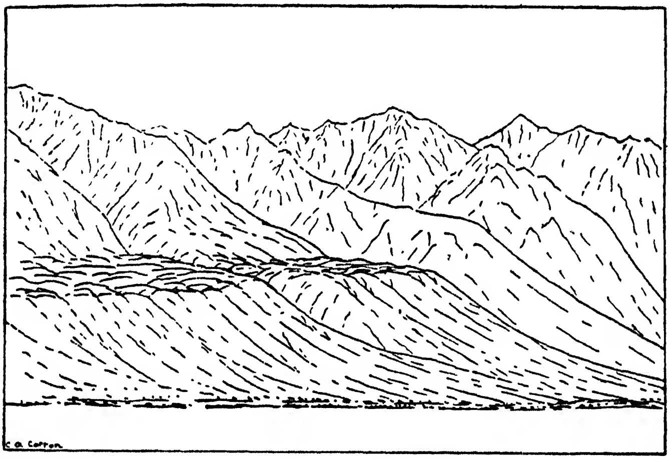

Fig. 134. Bench of stranded lateral moraine left by the shrinking Tasman Glacier, and now overlooking Lake Pukaki, New Zealand.

A stranded median moraine left by a small glacier of the Ice Age in the Sherwin Lakes cirque, in the Sierra Nevada of California, is described by Kesseli.[5]

A conspicuous lateral ridge which borders the great Tasman Glacier, in New Zealand, and has been very recently stranded owing to shrinkage of the glacier is made use of for some miles as a motor road. As described by Speight,[6] it "runs for some six miles

[5] J. E. Kesseli, Studies in the Pleistocene Glaciation of the Sierra Nevada, California, *Univ. Cal. Publ. in Geog.*, 6 (8), pp. 315-362, 1941.

[6] R. Speight, Ice Wasting and Glacier Retreat in New Zealand, *Jour. Geomorph.*, 3, p. 135, 1940.

as a fairly straight, narrow ridge, steep on both sides, but especially towards the glacier, where it is precipitous. Its height above the present glacier level varies between 150 and 200 feet. It is generally bare of vegetation . . . , and the whole surface condition suggests recent abandonment by the ice."

Such distinct ridges grade into terrace-like "lateral embankments,"[7] and these into mere veneers of moraine with little or no relief on the valley side. Broad embankments with a considerable development of "knob-and-kettle" (or hummock-and-tarn) relief flank the lower Tasman valley, from which the glacier has now withdrawn (Pl. LIV, 1). These morainic embankments are distinguished from "kame terraces" (p. 330) by their being deposits of unassorted glacial debris, not water-laid.

End Moraines

"Terminal" moraines, as the term is best defined, are the dumps of debris piled before the terminal faces of glaciers (and the long ice-fronts of continental glaciers) while these are stationary or nearly so. Some such accumulations form great barriers which impound lakes after the melting of the glaciers, and rock-basin lakes that result from glacial overdeepening have commonly been enlarged by the upbuilding of morainic barriers above the level of their bedrock rims.

A fairly common usage[8] restricts "terminal" to the description of the farthest advanced down-valley (or distally) of such barriers or ridges, and similar moraines dropped during pauses in the final retreat of the ice are then called either "recessional" or "stadial," but the distinction is of no geomorphic significance. To avoid ambiguity terminal moraines (in the broad sense) are sometimes called "end moraines."

The bulk and areal extent of terminal moraines are not related either to the size of the glaciers that deposited them or to the proportion of debris to ice in the glaciers, but rather to the competence or incompetence of the melt-water streams draining from the glaciers to pick up and carry away the debris as it is released

[7] J. L. Rich, Glacial Geology of the Catskills, *N.Y. State Mus. Bull.*, No. 299, p. 23, 1935.

[8] Condemned by Chamberlin and Salisbury, *Geology*, Vol. 3, p. 367, 1906.

from the ice. Large glaciers which carry enormous debris loads may be depositing insignificant moraines, but small glaciers that occupy hanging cirques and short valleys on the other hand commonly drop most of their debris as ridges, the older of which, in loop form, mark former outlines of the glaciers.

The morainic ridges nearest to cirque glaciers in the western United States have been observed to be disproportionately large, and this puzzling peculiarity has been explained by the discovery (in the case of the moraine of the Conness Glacier) that the ridge consists of stagnant ice merely coated with ablation moraine, which will eventually settle down into a ridge of normal dimensions.[9]

Ablation moraines of some very small glaciers recently in existence (though the ice has now melted out of them) remain as almost perfect reproductions of the original glaciers, so fully loaded were these with englacial debris.

Such is the explanation credibly advocated for features which have been termed "rock streams" and "rock glaciers."[10] These are stream-like or glacier-like piles of generally very coarse bouldery waste which exhibit tongue-like convex forms with the surfaces of the tongues corrugated in ridges parallel to the sides and fronts.[11]

The common assumption, based on their glacier-like form, that these relict landforms are streams still actively creeping down slopes[12] seems to be illusory. "Pronounced ridges and slopes that clearly separate different superposed parts of the blocky deposits can only be understood to have resulted from variations in size of the bodies of ice that originated the rock streams. The lower and shorter ridges that are in the main subparallel to the edges of the

[9] F. E. Matthes, Committee on Glaciers 1939-40, *Trans. Am. Geophys. Union,* p. 399, 1940.

[10] J. E. Kesseli, Rock Streams in the Sierra Nevada, California, *Geog. Rev.,* 31, pp. 203-227, 1941.

[11] To this category of landforms belong some ridged deposits of boulders in the Kaikoura Mountains of New Zealand which are the only traces of glaciation thus far described in that range (J. H. Rose, Probable Moraines, Inland Kaikoura Range, Marlborough, *New Zealand Jour. Sci. & Tech.,* 14, pp. 252-254, 1933).

[12] C. F. S. Sharpe, *Landslides and Related Phenomena,* pp. 42-46, 1938. Comparison of photographs taken seventy years apart yields evidence that such movement, if it ever took place, has ceased in rock streams of the Presidential Range, as has been pointed out by R. P. Goldthwait, Geology of the Presidential Range, *N.H. Ac. Sci. Bull.,* No. 1, Figs. 15, 16, 1940.

streams may well have resulted from a deformation of the deposit under the weight of the ice that passed over it."[13]

Glaciers without Conspicuous End Moraines

Among existing large glaciers which yield melt-water in sufficient abundance to carry away their debris loads the Tasman Glacier, in New Zealand, is a conspicuous example. The rather common absence of conspicuously heaped moraines ("in barrier form") on valley-floors may be explained, according to Speight, in the following ways: "(1) Such moraine has never been deposited, the terminal

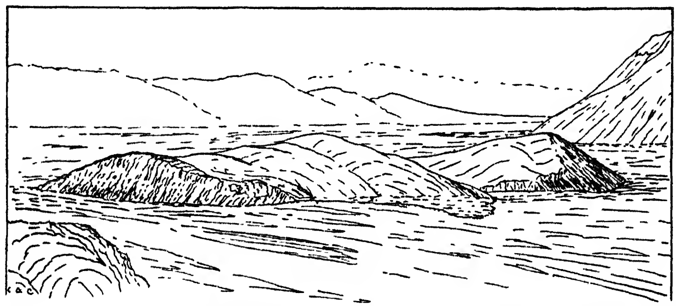

Fig. 135. Terminal moraine partly buried in outwash gravel and partly destroyed by river erosion. Sibbald's "Island" in the valley train of the Godley Glacier, New Zealand. (Drawn from a photograph.)

face having been always in a condition similar to that of the present face of the Tasman [Pl. XVII, 1] and other large glaciers of New Zealand; (2) A terminal moraine was deposited but destroyed subsequently by the action of the glacial stream [Fig. 135];[14] (3) The terminal moraine, if formed, was buried in the material brought down by rivers; (4) Deposition of the burden of debris has taken place by down-wasting, the covering material having just been dropped as the ice wasted away."[15]

The capacity of the outflowing rivers seems equal to the task of removing the enormous loads of debris delivered to them by New Zealand glaciers. Speight has noted that heavy summer

[13] J. E. Kesseli, *loc. cit.* (10), p. 227.

[14] This process of destruction is illustrated in a photograph of the North Iliamna Glacier, in Alaska, by H. B. Washburn, Jr. (*Geographical Journal,* 98, photo 6, opp. p. 226, 1941).

[15] R. Speight, Ice Wasting and Glacier Retreat in New Zealand, *Jour. Geomorph.,* 3, pp. 131-43, 1940.

flooding in these rivers is due only in part to melting of ice by the sun, for abundant rain falling on the glaciers both contributes water and melts ice. In Alaska also half an inch of rain falls daily over the Malaspina Glacier surface, and a conservative estimate of the run-off during the season of most rapid ablation would be four inches per day.[16]

The scantiness of terminal (and "recessional") moraines has frequently led to erroneous impressions regarding the quantities of material that have been transported by the valley glaciers and ice-sheets of the past, and of their capacity to denude the earth's surface. It is, therefore, somewhat important to bear in mind that heaped moraines accumulate in bulk not as a matter of course at all glacier termini but only where conditions are favourable. Either stagnation and "down-wasting" or rapid retreat of the ice-front of a wasting glacier which is well loaded with englacial debris will leave this spread as a sheet or in irregular low heaps over the floor in a broad strip. The conditions, on the other hand, favouring the piling of such material as a more conspicuous ridge or barrier may be found when the ice-front is stationary,[17] but a certain amount of advance at the time of deposit may have occurred and is perhaps more usual.[18] If this advance follows an episode of wastage by rapid ablation, abundant surface moraines will have been exposed on the marginal ice. During an advance "the ice shears and buckles in front and swells up behind" and "a relatively huge mass of material could be dumped over the steep front of the ice in a very short period."[19]

A contributing favourable condition is a local slope of the ground towards the ice front.[19]

[16] O. D. von Engeln, Phenomena Associated with Glacier Drainage and Wastage, *Zeits. f. Gletscherk.*, 6, pp. 148-149, 1911.

[17] "Only when the forward movement of the body of the ice and the down-wasting of its surface are so perfectly balanced that the ice margin does not alter its position, or are so nearly balanced that the margin shifts back and forth over a relatively narrow zone, will enough debris accumulate in one belt to constitute a marginal moraine. Terminal and recessional moraines thus mark halts in the movement of an ice margin." (D. J[ohnson], Normal Ice-retreat or Down-wasting? *Jour. Geomorph.*, 4, p. 90, 1941.)

[18] O. D. von Engeln, Large Sharply-defined Terminal Moraine Ridges, *CR. Congr. Internat. Géog. Amsterdam*, 2, pp. 210-213, 1938.

[19] O. D. von Engeln, *loc. cit.* (18).

The cores of some moraine ridges consist of compacted masses of boulder clay containing much fine material such as may be derived from the lower layer of englacial debris, but in most moraines deposited around the terminus of a glacier the characteristic material throughout is a mixture in which angular blocks are abundant, suggesting accumulation as a result of the "dumping-from-the-surface" process.[20]

End moraines may be pushed up into ridges in some cases by advance of the ice front, but there is generally very little evidence of this thrusting. Advancing glaciers more generally override moraines.

Moraine Loops

A common form assumed by end-moraine ridges is arcuate in plan, forming "moraine loops," which in some cases extend widely around the sites of former expanded snouts of glaciers that deployed over open ground (Pl. LIV, 2). Many of the great terminal moraines that hold up the levels of lakes in mountain valleys are of this kind. A notable example is that around the foot of Lake Garda, in northern Italy, where morainic ridges in concentric arcs cover a broad zone. "This accumulation assumes on the south side of the Alps a far greater thickness than on the north side, because it is concentrated over a less extended area" (A. Penck).

Narrow glacier snouts, including those of very numerous small mountain glaciers which have issued from corries, have also been enclosed by loops. In such cases especially, the side portions of loops are often referred to as lateral moraines. These are paired "high morainic ridges which advance from the mouth of the canyons . . . in the form of free embankments."[21] Unlike the stranded lateral moraines previously described, however, these deposits are closely related to end moraines. In some cases in Europe they are massive enough to form ridges 1000 to 2000 feet high. Such bulky deposits have accumulated gradually on a solid foundation after the manner of end moraines. The whole loop must, indeed, be regarded as the end moraine of the glacier. The ridges have been observed to contain material that has been embedded in the ice as

[20] O. D. von Engeln, *loc. cit.* (18), p. 212.
[21] J. E. Kesseli, *loc. cit.* (5).

well as debris dumped from the surface, however. Even abraded blocks of subglacial origin have been brought out by "the lateral motion of the ice from centre to side."[22]

Though glacier tongues are generally effectively contained and guided by the side portions of the moraine loops they have deposited, some remarkable cases of diversion into new courses making a sharp turn to right or left have been described in California. To explain most of these it is necessary to postulate a long interglacial interval after the formation of the first loop, during which stream erosion has prepared a broadly open lateral gap through this loop sufficiently large to accommodate and guide the course of the glacier tongue in a second glaciation.[23]

Terminal Moraines of Continental Glaciers

Both in North America and in northern Europe parts of the terminal moraines left by the continental glaciers of the Ice Age are conspicuous features. They extend for hundreds of miles continuously and form chaotic belts of low hills and undrained hollows several miles in breadth (Figs. 136, 137).

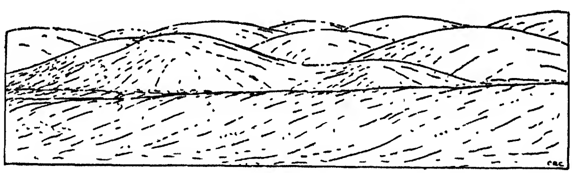

Fig. 136. The terminal moraine of a continental ice sheet in North America, at Oconomowoc, Wisconsin. (Drawn from a photograph.)

Pedestal Moraines

Some peculiar terminal features consisting of ground moraine have been built forward and upward so as to convert the glacial troughs (generally small and rather steep) behind them into hanging valleys; and similar deposits within valleys build steps. A typical example of these "pedestal" moraines[24] projects in front of the

[22] Chamberlin and Salisbury, *Geology,* Vol. 1, p. 303, 1905.

[23] J. E. Kesseli, *loc. cit.* (5).

[24] T. C. Chamberlin, Glacial Studies in Greenland, *Jour. Geol.,* 3, pp. 66-67, 1895. Also termed "embankments" (R. D. Salisbury, Salient Points Concerning the Geology of North Greenland, *Jour. Geol.,* 4, pp. 769-810, 1896; Chamberlin and Salisbury, *Geology,* Vol. 1, pp. 299-300, 1905). See also J. L. Rich, *loc. cit.* (7), pp. 32-36.

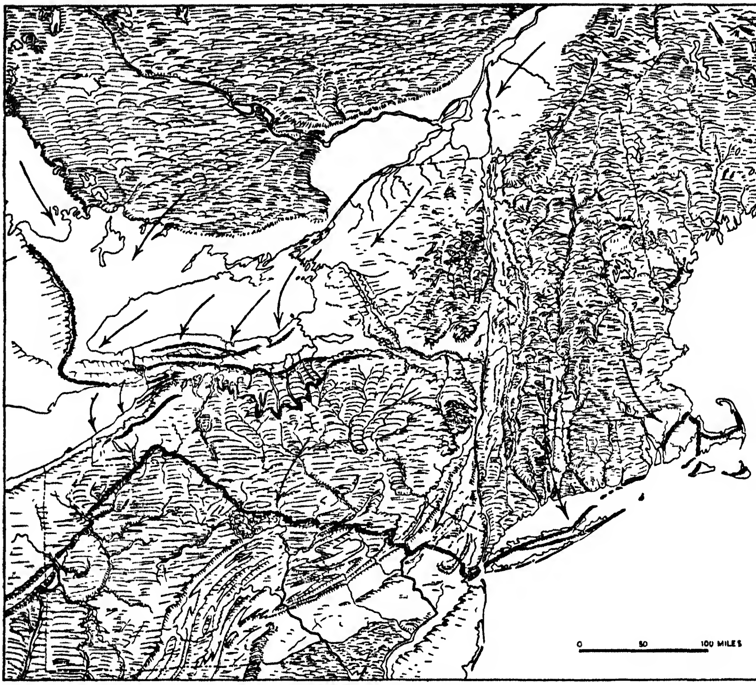

Fig. 137. Terminal moraine and "recessional" moraines of the last ice retreat in New England. Arrows show direction of ice-flow. (After Flint: *Geographical Review.*)

mouth of a small valley with a strong superficial resemblance to a rock bastion (p. 232). The method of accumulation is subglacial, as is indicated in Greenland pedestals figured by Chamberlin and Salisbury, in which overriding by ice is shown. In step-forming examples in the Catskill Mountains Rich has noted the presence of fringing rings of boulders which seem to have fallen from the snouts of the overriding glaciers. The pedestals themselves are composed of "till of the thick drift type" (Rich).

Ground-moraine Forms

The sheets of ground moraine spread widely over landscapes within the margins of ice sheets do not, where they are thin, alter the shapes of the buried landforms appreciably except where stream-

lined "tails" have accumulated in the lee of surviving rock knobs, combining with them to produce some of the smaller "crag-and-tail" forms (p. 245). Thick till deposits whether on level or hilly surfaces may be dissected by erosion and show a very much farther advanced stage of dissection than will be found on more resistant unburied bedrock surfaces, but even inclined surfaces of the permeable till are commonly found quite undissected. In such cases it must be assumed that the surface has been protected by vegetation from rainwash gullying.

Thick ground-moraine deposits will be made in association with thick accumulations of gravel if such are laid down by aggrading rivers of melt-water beyond the ice margin. Where an enormous load of ablation moraine and englacial debris comparable to that

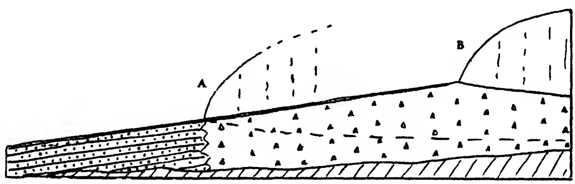

Fig. 138. Suggested deposition of ground moraine under the snout of the Tasman Glacier: A, when the front is stationary; B, when retreating.

now on and in the Tasman Glacier (Pl. XVII, 1) is carried by the marginal ice, and this material is supplied in such quantity to an outflowing river that it must aggrade its valley, the glacier snout will normally rise and ride upon a thick ground moraine[25] (Fig. 138).

Drumlins

Unusually thick ground moraine containing much clay may be moulded into relief forms termed "drumlins" (Pl. LV, 1), which are whale-backed, rather elongated hills with tapering tails like those of "crag-and-tail" features, but blunt at the stoss end. Average dimensions of drumlins are half-a-mile long, an eighth of a mile wide, and about 150 feet high. The form has been described as

[25] "The deepening of the distal part of the channel accomplished in youth might be followed by a shallowing for a time during maturity when the accumulation of morainal and washed materials in front of the glacier compelled its end to rise." (W. M. Davis, Glacial Erosion . . . , *Geographical Essays*, p. 668, 1909.) See also C. A. Cotton, Moraines and Outwash of the Tasman Glacier, *Trans. Roy. Soc. N.Z.*, 71, pp. 204-207, 1941.

"having a regular oval plan and a symmetrical half-egg shaped profile" (RICH).

Drumlins occur abundantly where marginal portions of continental ice-sheets spread over surfaces of small relief. In such regions there are "swarms" of drumlins all elongated parallel to one another and to the direction of ice movement, for example north and south of Lake Ontario (Fig. 139) and in eastern Wisconsin, where they are said to number ten thousand.

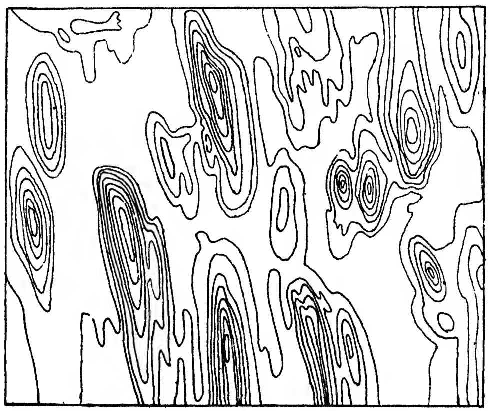

Fig. 139. Drumlins in plan, New York State. Contour interval 20 ft. Approximate scale, ⅞ in. = 1 mile.

Some drumlins in the lowlands of Scotland, it has been claimed, are elongated transversely to the flow of the ice sheet and have been developed in an unexplained way parallel to the prevailing wind direction.[26] Typically orientated drumlins occur in Europe, however, and in the Alpine region Penck and Brückner recognise as typical a zone of such drumlins within the arcuate morainic ridges which enclosed the ends of great glaciers of the Ice Age.[27]

Some forms classed as drumlins may be moulded out of older ground moraine that has been overridden by a newer ice sheet, but a more generally accepted explanation applicable to typical drumlins is that they are constructional forms built under the glacier ice not

[26] J. W. Gregory, Scottish Drumlins, *Trans. Roy. Soc. Edin.*, 54, pp. 433-440, 1926. In Ireland, however, this author has assumed that the elongation of drumlins indicates the direction of ice movement (*Phil. Trans. Roy. Soc.*, B 210, pp. 115-151, 1920).

[27] A. Penck and F. Brückner, *Die Alpen im Eiszeitalter*, p. 16, 1909.

far from its margin. Thus drumlins are described as a "specialised form of thick drift" laid down "where the debris load became so great as compared with the carrying power of the ice that some of it had to be deposited on the ground beneath probably by a plastering-on process."[28] Some drumlins ("rock drumlins") have cores of bedrock, however.

According to Case,[29] some drumlin swarms "lie in the lee of escarpments or other irregularities . . . over which the ice has passed," and these escarpments have caused currents in the continental glacier to pass upward and forward in the form of an arch. Following a suggestion of Chamberlin,[30] who has termed such an arch the "drumloidal curve," Case formulates a hypothesis in explanation of the deposit of subglacial debris in the form of drumlins, as follows:

> Arches would have under them regions of relatively smaller ice motion with consequent deposition of debris . . . If . . . the drift should become of sufficient thickness it might in spots clog up under the ice and become sufficiently resistant to cause upward currents . . . The elongation and building up of the drumlin would tend to keep the currents from descending and would lengthen the arch till drumlins two miles long might be formed as noted in New York.[31]

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[28] J. L. Rich, Glacial Geology of the Catskills, *N.Y. State Mus. Bull.*, 299, p. 31, 1935.

[29] E. C. Case, Experiments in Ice Motion, *Jour. Geol.*, 3, pp. 918-934, 1895.

[30] T. C. Chamberlin, Recent Glacial Studies in Greenland, *Bull. Geol. Soc. Am.*, 6, p. 216, 1895.

[31] E. C. Case, *loc. cit.* (29), pp. 932-933.

CHAPTER XXIV

Proglacial Accumulations and Drainage Modifications

THE LARGER proportion of the glacial "drift" (or glacially transported material) before it has come to rest has been carried also by melt-water streams for at least a short distance and has been laid down as "fluvioglacial"[1] deposits, the forms and internal structures of which resemble more or less closely those of the water-laid deposits built by aggrading rivers in non-glaciated regions and those deposited on the floors and around the margins of lakes. The streams of water that result from the melting of glacier ice have been flowing under pressure in ice-tunnels, however, and gush out from the mouths of these fully loaded with gravel, sand, silt, and rock flour. In some cases they have debouched below the water level in lakes bordering the ice front.

Fluvioglacial drift materials, being water-carried, are also water-sorted, more especially those discharged into standing water, and when laid down are stratified either with lake-floor and deltaic bedding or with the less regular lens-and-pocket arrangement characteristic of river-laid alluvium, though the gravel may be transported but a short distance and be so little affected by stream wear that some pebbles still retain a glaciated form and glacial markings.

Fluvioglacial gravel and sand have accumulated and built characteristic "proglacial" landforms in the vicinity of the ice front, especially where the glacial load has contained a large proportion of coarse material. A preponderance of clay in the glacial debris will result in the transportation of it much farther afield by rivers and in an apparent dearth of proglacial features; but where lakes fringe the ice front they provide settling basins for much fine material as well as coarse. Proglacial forms built of fluvioglacial drift may be described under two heads, namely, the stream-laid (alluvial) fans and aggraded plains, generally termed "outwash aprons" and

[1] Or "glaciofluvial."

"valley trains", and those deposited in standing water ponded at the ice margin.

Proglacial Aggraded Plains

The older river-built proglacial features (aggraded outwash plains or valley trains), as distinguished from those now growing in front of existing glaciers, are commonly trenched and terraced by erosion. Some are also very extensively pitted owing to the gravels composing them having been deposited over and around detached ice masses which have afterwards melted.[2] In general the hollows resulting from this cause, whether in fluvial outwash or in the deposits laid down in ice-marginal lakes (Fig. 147), are termed "kettles" (Pl. LVI, 2). Both bowl-like round pits and elongated trench-like kettles are common, the latter generally marking the positions of shallow valleys in the surface of the underlying bedrock, in which residual strips of wasting ice have lingered long enough to be buried. In places kettles are so abundant that no level-surfaced remnants of the drift-built landforms are left among them. Very great irregularity of surface (knob-and-kettle forms) may be the result of deposit of the outwash gravel on continuous ice, generally of varying thickness, the melting of which has afterwards let down the gravel deposits.

While much of the dissection of valley trains is postglacial and results from lowering of local base-levels due to various causes, some may follow immediately on a withdrawal of the ice front to a new line and a consequent shifting of the zone of outwash deposition. Some pitted terrace treads are found in the trenched and terraced valleys cut below the level of outwash plains, and these can be explained only on the hypothesis that dissection accompanied by terracing of the outwash has occurred before outlying gravel-buried ice masses have melted. The doubtful theory that extensive general dissection of outwash plains goes on contemporaneously with their extension in the direction of a retreating ice front is based on the over-generalised doctrine that "decrease in load is a normal consequence of recession of the ice margin and was accompanied by a decrease of the stream grade."[3]

[2] F. T. Thwaites, The Origin and Significance of Pitted Outwash, *Jour. Geol.*, 34, pp. 308-319, 1926.

[3] F. T. Thwaites, *loc. cit.* (2), p. 312.

Dissection of an outwash apron has been explained also by assuming the opening of a "moat" between a new ice margin and an "ice-contact" slope along the line of former contact between ice and outwash that has been banked against it; but ice-contact features are rarely recognised in ancient valley trains.

Enormous outwash trains in the valleys of the Tasman and a number of other New Zealand glaciers are undissected and are still in course of aggradation although the glaciers have retreated far up the valleys[4] (Pl. LV, 2), and this seems to indicate that commonly such a falling-off in the supply of waste as may result in valley-floor trenching is delayed until the glacier melts away altogether. There is at present a very heavy load of ablation moraine and englacial debris on and in the snout of the Tasman Glacier (Pl. XVII, 1)—and, indeed, the same is true in the case of most existing glaciers outside the polar regions. It seems probable, therefore, that, as the surface of a valley train is built up, much ground moraine may be deposited beneath the glacier so as to raise it to the level of the outwash (p. 325). This may take place whether the ice front is stationary (Fig. 138, A) or retreating (B). During retreat, however, the ground moraine will be veneered with and hidden by outwash gravel. Where a large supply of debris is continuously maintained, it is improbable that degradational episodes alternating with upbuilding of outwash gravel will be at all common.

Kames and Kame Terraces

The features termed "kames", most of which are mounds grouped in irregular terraces (Pl. LVI, 1), are, as strictly defined, stream-built; but some of the forms classed in this rather heterogeneous category are claimed to have originated as deposits in standing water.[5]

"Kame terraces" (Pl. LVI, 1) and "lone kames" may have originated in different ways. The former, as defined by Salisbury, are "terraces of sand and gravel deposited by a glacial stream

[4] The Tasman Glacier has retreated 40 miles, and its valley train is 25 miles long (to the head of Lake Pukaki).

[5] J. W. Gregory, The Scottish Kames . . . , *Trans. Roy. Soc. Edin.*, 54, pp. 395-432, 1926; T. C. Brown, Kames and Kame Terraces in Massachusetts, *Bull. Geol. Soc. Am.*, 42, pp. 467-480, 1931.

between valley ice (generally stagnant) and the rock slope of the valley."[6] Of this character are the "marginal kames" described by Rich[7] as hummocky deposits along hillsides. Owing to the fact that some terrace forms built in standing water where it was held up by ice dams have been described as "kames" or "kame terraces" Flint[8] has proposed to abandon the term altogether.

"Kames", according to Rich, however, for whom the term has a definite meaning, have in general, "the form either of isolated cone-shaped mounds or of irregular mounds and hollows. They are distinguished from moraines by their gravelly composition and 'knob-and-kettle' topography; from deltas by their lack of flat

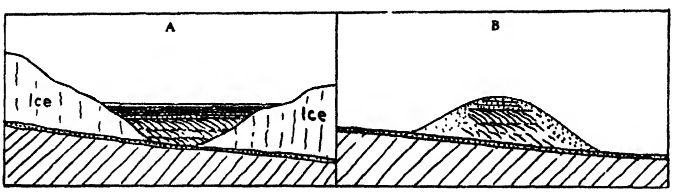

Fig. 140. Origin of the structure and form of a lone kame. A, deltaic deposit in a bay in the ice-margin; B, slumping of the sides has taken place after the ice has melted, covering the deltaic-bedded sands with a layer of gravel. (After Brown.)

tops; and from eskers, which are long, narrow winding ridges and are composed of the same material they are distinguished by their form."[9] Some of the knob-and-kettle groups of "kame moraines", as these have been termed, were deposited where sub-glacial streams discharged from ice tunnels below the surface in marginal lakes.

"Lone kames" (Rich), which are the isolated conical forms, were originally laid down possibly on the ice in holes or caverns, or in bays in the ice front[10] (Fig. 140).

[6] R. D. Salisbury, *Glacial Geology of New Jersey*, 5, pp. 121-123, N.J. Geol. Surv., 1902.

[7] J. L. Rich, Glacial Geology of the Catskills, *N.Y. State Mus. Bull.*, 299, p. 41, 1935.

[8] R. F. Flint, *The Glacial Geology of Connecticut*, p. 103, Hartford: 1930.

[9] J. L. Rich, *loc. cit.* (7), p. 40.

[10] T. C. Brown, *loc. cit.* (5).

Eskers

Symmetrical elongated ridges (Figs. 141, 141A) composed of stratified sand and gravel which are known as "eskers" are, as noted by Rich (above), distinguished from kames by their long, narrow winding-ridge form, which makes them, where perfectly developed, the most remarkable of the landforms built of fluvioglacial debris;

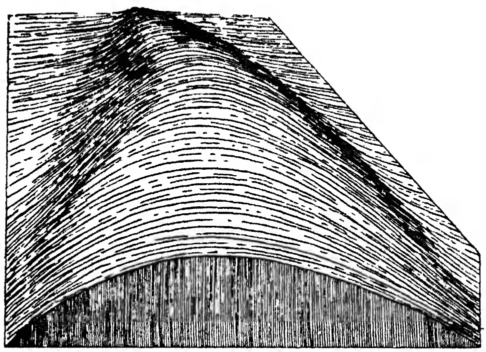

Fig. 141. Profile of an esker in Finland. (Drawn from a photograph.)

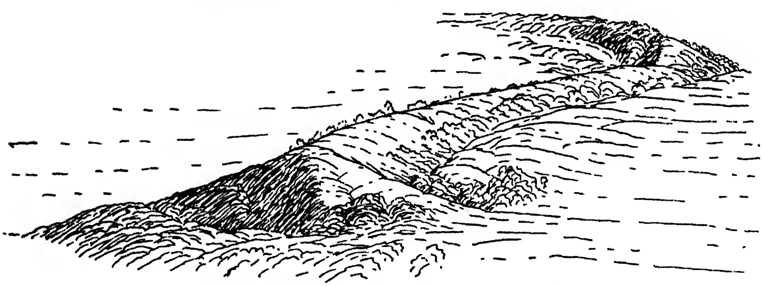

Fig. 141A. An esker in Minnesota. (Drawn from a photograph.)

for not only do they wind about in plan (Pl. LVII, 1), but even pass up and down over irregularities of the valley-floors and lowlands upon which they have been built. These peculiarities are satisfactorily explained, however, by the generally accepted hypothesis of esker construction, which is as follows:

> Subglacial streams emerging at an ice foot in the deep water of a lake built . . . deposits in the form of gravel ridges known as "eskers" . . . These were partly constructed in the

> tunnels under the ice and partly as hummocks of material abruptly thrown down where emergence into standing water caused stream flow to cease. Progressive deposition as the ice front retreated made some eskers many miles long . . . and they were often built by waters flowing in a direction opposite to the present drainage.[11]

Eskers are associated with lake-floor silts and deltas (Fig. 147), in some cases being partly buried by these deposits.

As very long eskers of perfect form are known in Finland and Sweden, some prefer to employ the Swedish name "ose"[11a] (singular) instead of "esker", but in English writings, as established by American usage, "esker" is now firmly attached to these features, in spite of the fact that few of the "eskers" of Ireland, where the name originated, are true to type, for it would seem that most of the features known collectively by this name in Ireland must be placed in the category of ice-marginal kame-like terraces and ridges and mesa-like related forms.[12]

It is probable that some esker-like ridges, which may be difficult to distinguish from true eskers, are the slumped moulds of "crevasse-fillings"[13] which accumulated either on or between remnants of stagnant or almost stagnant ice, and are thus related in origin to lone kames.

Deposits in Proglacial Lakes

The features built of fluvioglacially derived material deposited in standing water constitute an important group. In the Scandinavian region some of these forms were constructed in the sea, but elsewhere they are mainly of lake origin.

Temporary "proglacial" lakes are common features of the margins of continental glaciers, especially when the volume of ice is shrinking as a result of climatic amelioration, and more especially where there is a general retreat of the ice margin in

[11] R. J. Lougee, Geology of the Connecticut Watershed, *N.H. Fish and Game Dept. Biol. Surv. Rep.*, 4, p. 136, 1939.

[11a] Anglicised form adopted by M. Sauramo, The Quaternary Geology of Finland, *Bull. Comm. Géol. de Finlande*, 86, 1929.

[12] J. W. Gregory, The Irish Eskers, *Phil. Trans. Roy. Soc.*, B 210, pp. 115-151, 1920; R. F. Flint, The Origin of the Irish "Eskers," *Geog. Rev.*, 20, pp. 615-630, 1930.

[13] R. F. Flint, Eskers and Crevasse-fillings, *Am. Jour. Sci.*, 15, pp. 410-416, 1928.

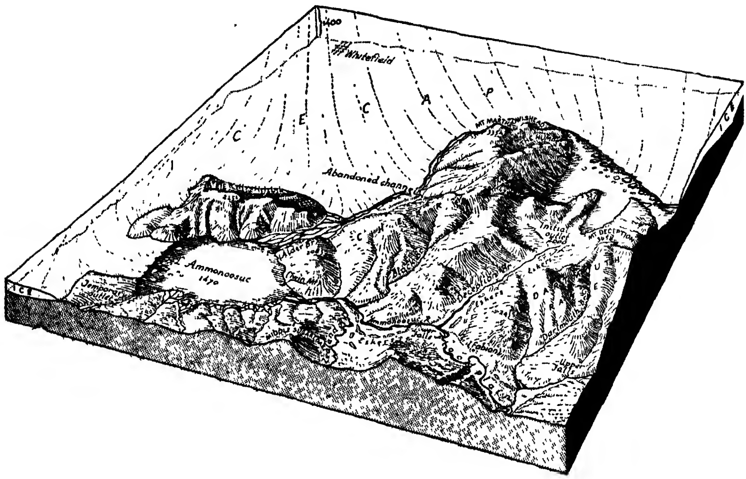

Fig. 142. Ponding of proglacial lakes in New England during the withdrawal of the North American continental glacier. (After Lougee: *Journal of Geomorphology*.)

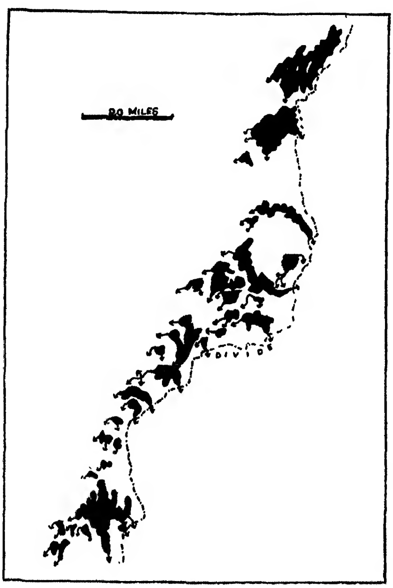

Fig. 143. Some of the ice-dammed lakes which existed temporarily in the Connecticut River basin, New Hampshire, during the dissipation of the last North American continental glacier. Spillways — in most cases several at successively lower levels—are shown by arrows. (After Lougee.)

progress due to this cause which exposes a land surface with a regional slope towards the ice. In a region of small relief—the American Middle West, for example—a few lakes of enormous size have been impounded; but where there is stronger relief the lakes are smaller and very much more numerous (Figs. 142, 143). Another possible cause of lake-impounding is the "down-wastage" by ablation of a stagnant ice sheet or of such portions of a continental glacier as have become isolated by combination of rapid local wastage with the configuration of the underlying land surface.

The former floors of temporary lakes, and also in some cases of marginal seas, have become plains—where open water was not encroached on by marginal delta deposits. These were built up of silts in which are recognised the annually alternating sand and clay layers known as "varves", from the counting of which much information has been obtained regarding the chronology of late Glacial times. Most of the lake-floor plains are now trenched by streams and some of them are considerably dissected.

Shorelines

The shorelines of lakes which have endured for long enough with fixed levels determined by the elevations of available outlets (spillways), are marked in many cases by conspicuous wave-cut and wave-built terraces. Though originally strictly level, these shore-line terraces have not uncommonly been tilted subsequently to their formation by the crustal upwarping which has taken place as a result of postglacial relief from the ice load of the Glacial Period. The naturally-marked contour lines traced by former water levels are still prominent after warping has occurred, and their inclinations can be measured, affording data which yield much information regarding the movements that have affected the lake shores. That warping was already in progress during the existence of some of the lakes is indicated by the fact that successively incised beach terraces are not in all cases parallel to one another.

Perhaps the most celebrated examples of shoreline terraces which clearly indicate the former presence of an ice-margin lake are the Parallel Roads of Glen Roy, in Inverness-shire, Scotland. After the branching glens of the Glen Roy system had been shaped

into catenary trough forms (Pl. LVII, 2) by glaciers discharging into the larger Glen Spean the ice melted out of them, though lingering still in the main valley. Held up for a time by the dam formed by the Glen Spean ice a branching lake occupied Glen Roy and stood at the three successive levels which are still marked by shoreline terraces (Fig. 144 and Pl. LVII, 2).

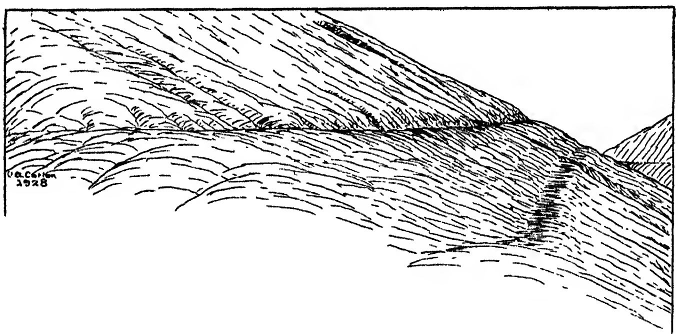

Fig. 144. Two shoreline terraces of the Glen Roy ice-dammed lake.

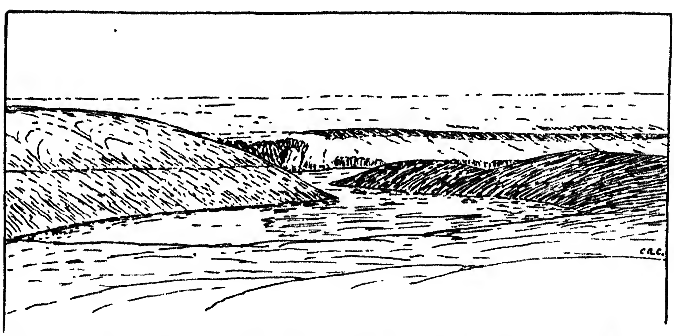

Fig. 145. A small ice-marginal lake in Novaya Zemlya with a shoreline terrace which marks a former high level of the lake. (Drawn from a photograph.)

The shoreline character of the Parallel Roads was recognised by Charles Darwin, but in his day the traces of Ice Age glaciation had not been deciphered, and these shoreline features were at first interpreted as indicating the former presence of an arm of the sea.

The somewhat hackneyed small-scale modern parallel of the great ice-dammed lakes of the past which is afforded by the tiny Märjelensee, at the side of the Aletsch Glacier in Switzerland, can now be reinforced by much larger examples of proglacial lakes bordering ice-sheets in Greenland (Pl. LVIII, 1) and Novaya Zemlya (Fig. 145).

Proglacial-lake Deltas

Among characteristic features of glacial drift in regions where proglacial lakes have existed are many terrace-like and mesa-like forms with either well preserved or somewhat dissected flat or kettle-pitted tops (Pl. LVI, 2), which are, at least internally, of deltaic construction, as is shown by their fore-set bedding of well washed sands. The deltaic fore-set beds grade into or rest on the varved (bottom-set) lake-floor silts and are covered by top-set gravels. Small water bodies have been completely filled with such stratified drift beds and converted into plains, but commonly only partial filling of larger lakes has taken place, producing forms which remain in the present-day landscape as terraces with fronts that preserve the fore-set slopes of deltas.

In other cases, however, terrace fronts are described as ice-contact slopes related to and moulded on the irregularities of the margins of stagnant ice slabs against which deltaic deposits have been banked.

Two theories have been proposed to explain the manner in which the ice sheet melted from New England. According to one of these, the theory of "normal retreat,"[14] the discrete-delta form may be expected to occur rather generally in the terraces of deltaic-bedded materials which are common in that region. Such deltas have somewhat crenulate ("lobate") margins, having been built forward in a number of distinct lobes by distributing streams (Fig. 147—the southern slopes).

Ice-margin Terraces

According to the other theory the marginal ice, instead of continuing to push forward as a "live" glacier (though melting back more rapidly than the ice advanced) became detached (or parts of

[14] See especially R. J. Lougee, Deglaciation of New England, *Jour. Geomorph.*, 3, pp. 189-217, 1940.

it became detached) from the region of alimentation and afterwards wasted away as stagnant ice slabs. Masses of stagnant ice remaining in main valleys would not only dam up lakes in tributary valleys, but would be bordered also by strips of ponded water, the levels of which would change as the ice melted away. The filling-in of these marginal lakes with sand and gravel would result in the building of terraces bearing a certain relationship to some forms that have been classed as kame terraces, but with generally flat (or kettle-pitted) treads and characterised particularly by "ice-contact" fronts which mould the irregular embayments and promontories of the corroded stagnant-ice margin along which deposit took place (Fig. 146); but the effects of slumping which accompanied and

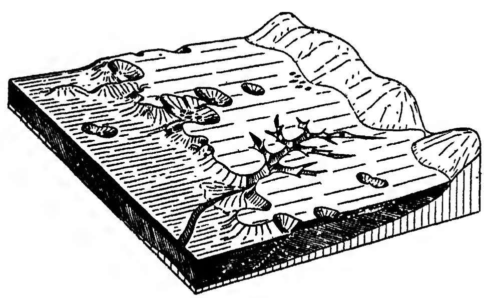

Fig. 146. Two terrace treads marking the levels of deltaic infilling in ice-marginal waters at successive levels. The front of the upper terrace (the only terrace-front shown) shows ice-contact forms. The gap in the hills at the right is the spillway that controlled the higher lake level. "Note the bedding fore-set toward the spillway. The lower terrace rests against the higher one, and its bedding indicates a spillway situated somewhere in the direction of the observer." (After Flint: *Geographical Review.*)

followed the melting of the ice may blur these outlines considerably (Pl. LVI, 1).

Ice-marginal terraces built in long narrow marginal (valley-side) lakes will stand at a uniform elevation for considerable distances, thus affording a distinction from river-cut terraces with down-valley gradients.[14a] In detail, however, the treads will not conform to the water level, nor will the terraces consist of sandy deltaic beds throughout. Like discrete deltas they are capped by gravelly top-set beds (Fig. 146) which must have fan-like top-set surfaces.

[14a] R. F. Flint, The Stagnation and Dissipation of the Last Ice Sheet, *Geog. Rev.*, 19, pp. 256-289, 1929.

Distinction from discrete-delta terraces depends upon recognition of the ice-contact slope which has moulded the ice margin. Where true deltas with free lobate margins and ice-contact terraces of deltaic materials are both present their differentiation is a matter of considerable difficulty.[15]

In some cases successive ice-marginal terraces have been described which have been built in water up to the levels of successively opened spillways (Fig. 146).

Glacial "Sand Plains"

Many mesa-like features were built out into proglacial lakes as deltas in front of an ice margin by streams emerging below the water level from tunnels but too heavily charged with debris merely to build eskers. Melting of the ice left these deltas as isolated table-topped forms which, being no longer traversed by streams, have largely escaped postglacial dissection.[16]

Such "glacial sand plains" have lobate margins at the distal (fore-set) border, to which fore-set beds in the interior structure are parallel, while at the proximal margin they may preserve the form of the ice contact, though generally this face is very irregular and is pitted with kettles (Pl. LVI, 2). The bedding under it is of the kind termed by Davis "back-set"—somewhat irregular, but with dips consistently in the direction from which the water-deposited debris was supplied. An esker deposited along the former feeding channel may still remain attached to the delta like a stem to a flower. The features mapped in Fig. 147 are of this origin.[17] The delta figured is half a mile square. Its "surface rises gently northward to the location of the former ice front, where it is terminated by bouldery ice-contact slopes surmounting a kame area containing kettle holes of various sizes . . . . Connecting with the northern margin of the kame area there is a feeding esker."[18]

[15] "It took six weeks of mapping to disprove stagnant ice in one locality" (R. J. Lougee, Stagnation of Ice in Connecticut, *Science,* 91, pp. 69-70, 1940).

[16] W. M. Davis, Structure and Origin of Glacial Sand Plains, *Bull. Geol. Soc. Am.,* 1, pp. 195-202, 1890.

[17] R. J. Lougee, Physiography of the Quinnipiac-Farmington Lowland in Connecticut, *Colby Monographs,* 7, p. 38, 1938. Compare W. M. Davis, *loc. cit.* (16), Pl. 3.

[18] The stem-and-flower relation of an esker to a delta (or fan) is shown remarkably clearly in a group of recently built forms in front of the retreating Woodworth Glacier, Alaska, as photographed by H. B. Washburn, Jr. (*Geographical Journal,* 98, photo 8, opp. p. 227, 1941).

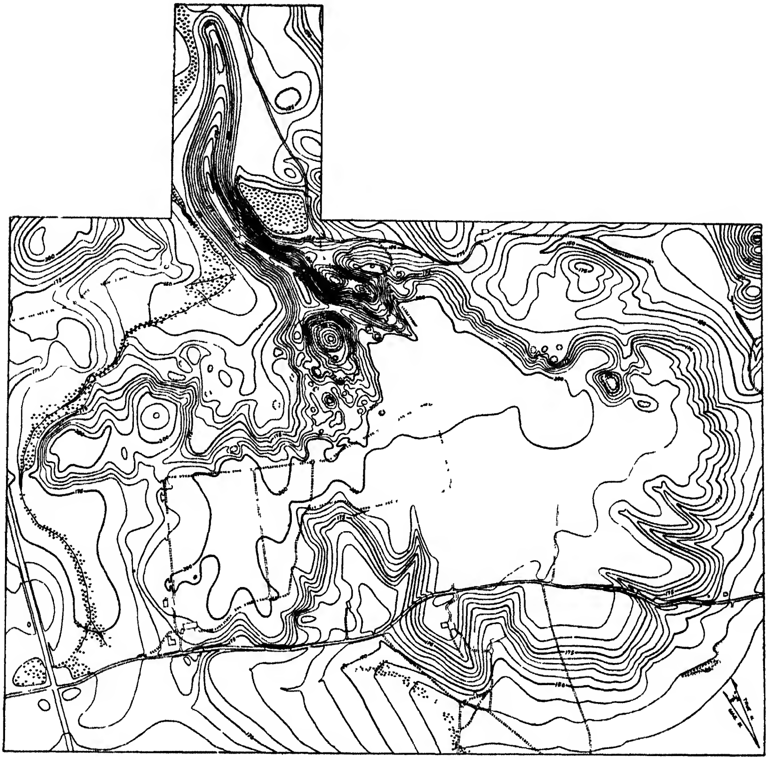

Fig. 147. An ice-marginal delta at Cheshire, Connecticut, which was built southward with a lobate margin into a proglacial lake. (Approx. scale: 5 ins. = 1 mile.) (After Lougee.)

The close relation of the esker, which marks the position of the ice tunnel that served as a feeding channel, to its distal (proglacial) delta or "sand plain" expansion is expressed thus by Lougee:

"Eskers seldom grew much above static water levels, tending rather to spread out in the form of flat-topped proglacial deltas wherever localised deposition building up to the water level was long continued."[19]

The Irish "Eskers"

The hypothesis of deposition of sand and gravel mainly with deltaic structures in lakes associated with wasting bodies of stagnant

[19] R. J. Lougee, *loc. cit.* (11), p. 136.

ice has been employed in an explanation of the origin of the widespread features of very variable form and outline which are known generally in Ireland as "eskers." Among these may be some eskers in the strict sense in which the term has come to be used with very general consent (pp. 332-3).[20] But the Irish drift features have generally assumed forms quite different from these and must have originated in a different way. Flint[21] explains them as deltaic deposits of the debris derived by melt-water streams from stagnant ice slabs around and among which water was ponded. As the last remnants of ice lay in shallow valleys of the land surface, the

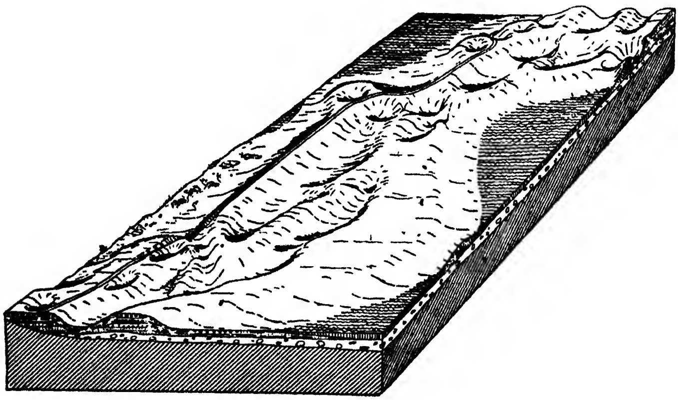

Fig. 148. Constructional drift landforms (so-called "eskers") in King's County, Ireland. (After Flint: *Geographical Review*.)

constructive features built of drift are now found either on the divides between these or on valley sides. These very abundant ice-marginal features in Ireland are described as: "elongate ridges, isolated mounds and hummocks, and broad flat-topped masses" (Fig. 148). "The heights of all these forms, regardless of their shape in ground plan, range from about 30 up to nearly 100 feet above the ground on which they rest . . . . [making them] visible for miles across the bogs and plains that separate them. . . . All the forms are alike in respect to their sides. Their slopes form angles

[20] J. K. Charlesworth, The Glacial Retreat from Central and Southern Ireland, *Quart. Jour. Geol. Soc.*, 84, pp. 293-344, 1928.

[21] R. F. Flint, The Origin of the Irish "Eskers", *Geog. Rev.*, 20, pp. 615-30, 1930.

of from 25 to 35 degrees, and thus lie at or near the angle of rest for the material of which they are composed."[22]

Proglacial Drainage Changes

Changes in river courses as compared with the courses followed in preglacial times have been brought about in various ways by glaciation, but some of the most striking changes resulted through the deepening of the spillways from proglacial lakes as gorges which still carry away the drainage from considerable areas, though numerous notches cut in high-level spillways were afterwards abandoned and remain as air gaps in the landscape. Both in England and in North America many examples are known of drainage diversion due to proglacial ponding; and another fruitful cause of stream diversion has been the "plugging" of former river channels by thick masses of ground moraine, especially where the courses of preglacial rivers have been transverse to the direction of ice movement.

One kind of temporary diversion of drainage, which in some cases has become permanent also, has resulted from the formation of ice-marginal rivers instead of proglacial lakes. It was in such marginal rivers flowing between ice fronts and land slopes that typical kames were deposited. Where rivers flowed in preglacial courses down regional slopes descending northward towards the margin of a northern ice sheet rivers of considerable volume might turn aside along courses either actually marginal or close to and parallel with the ice margin, and might enlarge these new courses to become broad mature valleys across an easily eroded terrain. In Germany such valleys were opened out by rivers in temporary courses which were abandoned later when withdrawal of the North European ice sheet had re-exposed valleys opening northward and rivers reverted to lines of preglacial drainage. The ice-marginal valleys contain at present, therefore, only underfit streams, of which the River Spree is an example.

Notches cut across spurs by small ice-marginal streams are common in some glaciated regions. Besides leaving in some cases the "epiglacial" bench-like features referred to in Chapter XXI

[22] *Loc. cit.* (21), p. 618.

temporary ice-margin streams frequently cut gorges (Pl. LVIII, 2) and notches which remain afterwards in the landscape as air gaps

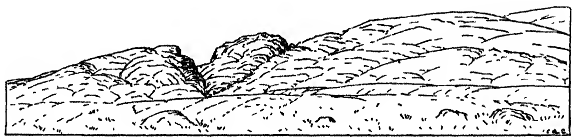

Fig. 149. Air-gap notches in a spur, which are the channels cut by former ice-margin streams, Gallatin Range, Montana. (From a photograph by L. Horberg.)

(Fig. 149). In some cases such ice-margin streams have overflowed from proglacial lakes. Many examples of such are known in northern England, notably in the Cleveland Hills of Yorkshire.[23]

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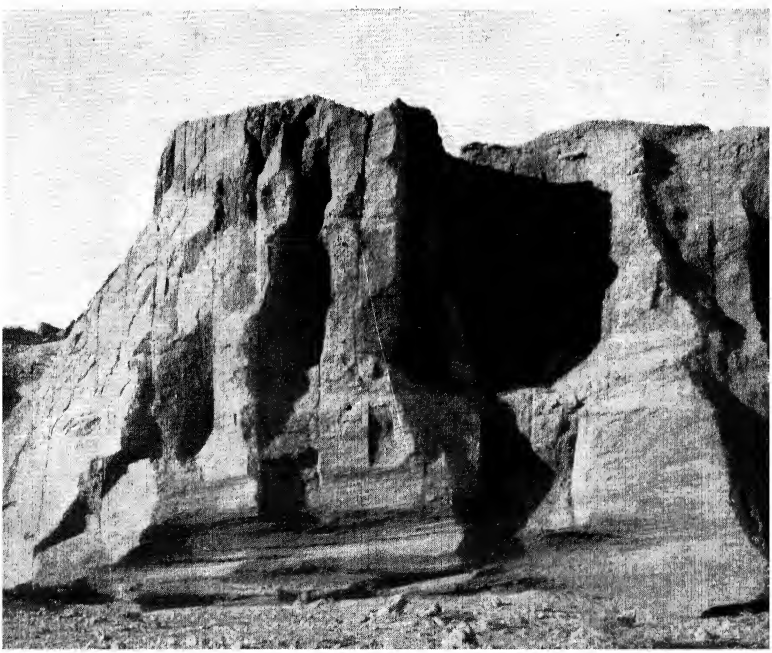
[23] P. F. Kendall, A System of Glacier Lakes in the Cleveland Hills, *Quart. Jour. Geol. Soc.*, 58, pp. 482-483, 1902.

Photo from N.Z. Dep. of Agriculture.

1. Tors of schist rock scoured and undercut by aeolian abrasion, which has been stimulated by recent depletion of the natural vegetation, Central Otago, New Zealand.



American Museum of Natural History: Dr. Walter Granger, photo.

2. The base of a cliff at Djadokhta, Mongolia, polished and grooved by aeolian abrasion.

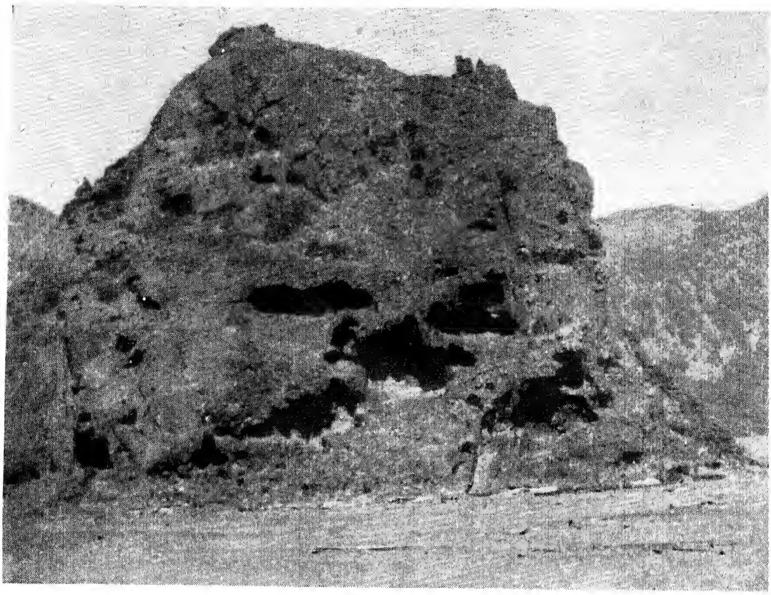
Plate II

Professor Eliot Blackwelder, photo.

1. Yardangs developed by wind scour in soft lake-bed deposits, Rogers Dry Lake, Mohave Desert, California.

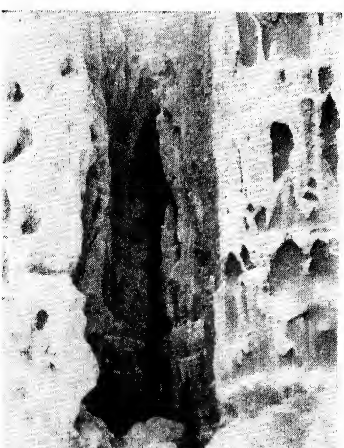
Professor Eliot Blackwelder, photo.

2. Tabular residuals in lake-bed deposits subject to aeolian deflation, Danby Dry Lake, California.



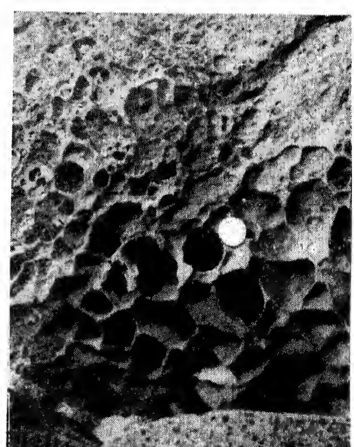
Professor J. A. Bartrum, photo.

1. Cavernous weathering (tafoni) in a cliff (150 feet high) steepened by marine erosion but no longer undercut by the sea, north of Manukau Harbour, New Zealand. The rock is volcanic breccia.



F. H. Clift, photo.

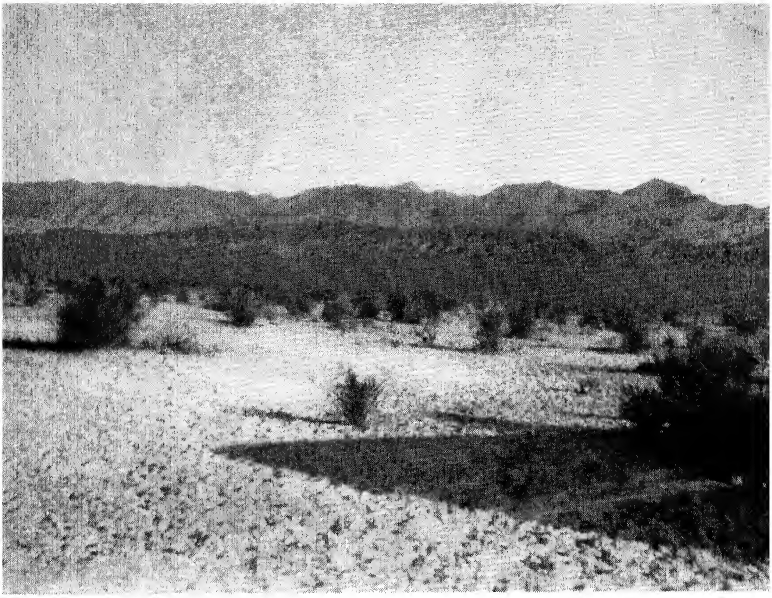
2. Cavernous weathering (tafoni) in a cliff of conglomerate near the sea, White Bluffs, Marlborough, New Zealand.



Professor J. A. Bartrum, photo.

3. Honeycomb weathering in basalt at the seashore, Takapuna, Auckland, New Zealand.

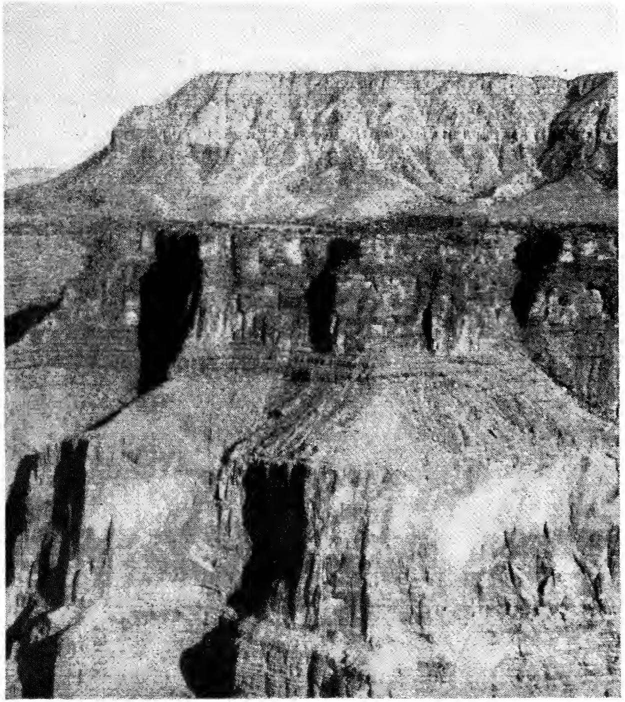
Plate IV



1. Young or early-mature stage of the mountainous-desert cycle, Death Valley, California. Somewhat leached salt of a dried playa floor is in the foreground.

2. Mature dissection of desert mountains, south of Phoenix, Arizona.

Plate V

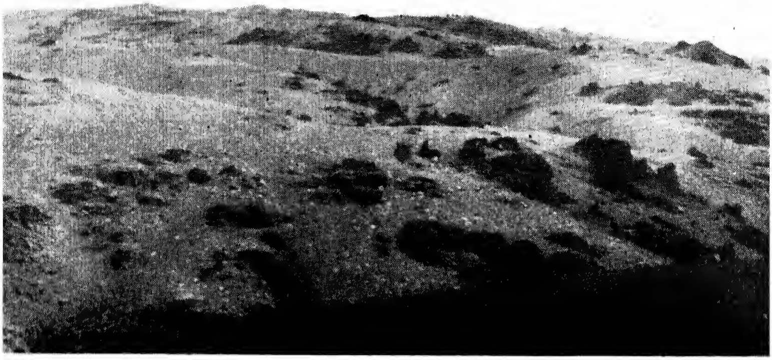


1. Sharp-edged structural terraces bordering the Grand Canyon of the Colorado, Arizona. (After W. M. Davis.)

U.S. Geol. Survey: N. H. Darton, photo.

2. Badlands developed by gullying erosion in a semi-arid region, Scott's Bluff, Nebraska. (Reproduced by permission.)

Plate VI



1. Ungraded slopes on a dissected surface of small relief in a semi-arid district, Raggedy Range, Central Otago, New Zealand.

W. H. Bradley, photo.

2. Exceptionally steep *rock* fans (thinly veneered with gravel) fringing an escarpment in Wyoming.

1. A "boulder-controlled" slope on granite, Silver Mountain, Mohave Desert, California. (After W. M. Davis, *Bull. Geol. Soc. Am.*)

2. A small mountain residual reduced in area by desert erosion, Camel Mountain, Arizona.

Plate VIII

Frasher's, Pomona, photo.

1. Desert sand dunes in the tectonic basin of Death Valley, California.

V. C. Browne, photo.

2. Sand drifts and wandering dunes, Hokianga North Head, New Zealand.

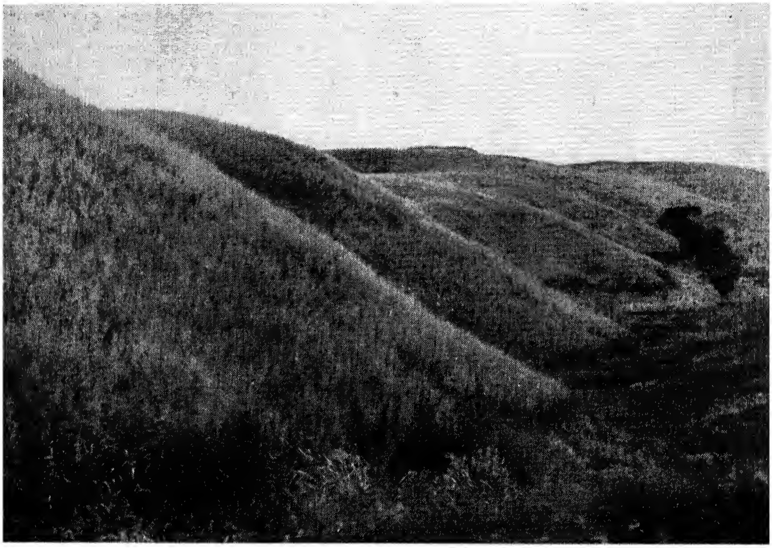
U.S. Geol. Survey: G. K. Gilbert, photo

1. Barchans at Biggs, Oregon. (Reproduced by permission.)

F. G. Radcliffe, photo.

2. A sandfall blocks a small stream so as to form a lake, near Auckland, New Zealand.

Plate X



L. Cockayne, photo.

1. A transverse dune ridge with leewardly-projecting tongues, west coast of Wellington, New Zealand.

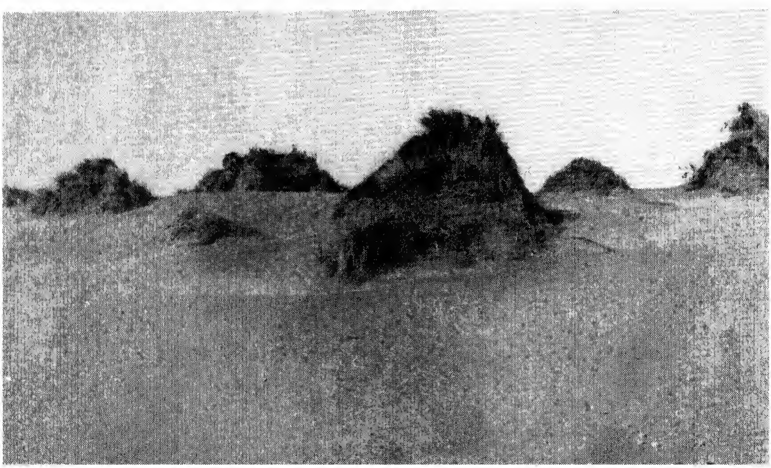


Photo from N.Z. Dep. of Agriculture.

2. The contest between vegetation and deflation. Wind-scoured gaps have reduced a ridge to irregular mounds, western Wellington, New Zealand.

Plate XI

M. C. Lysons, photo.

1. The névé, or snow-catchment area, of the Fox Glacier, New Zealand.

F. G. Radcliffe, photo.

2. Hanging glaciers on the Minarets Range and screes of avalanche ice feeding the Tasman Glacier, New Zealand.

Plate XII

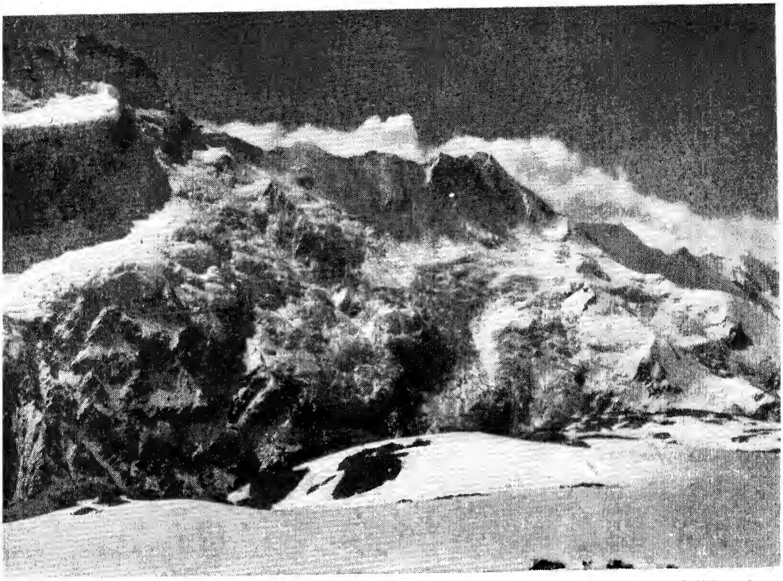
J. Gaberell, photo.

1. Confluence of glaciers produces median moraines in the Monte Rosa Group, European Alps. Bergschrunds are seen in the foreground.

M. C. Lysons, photo.

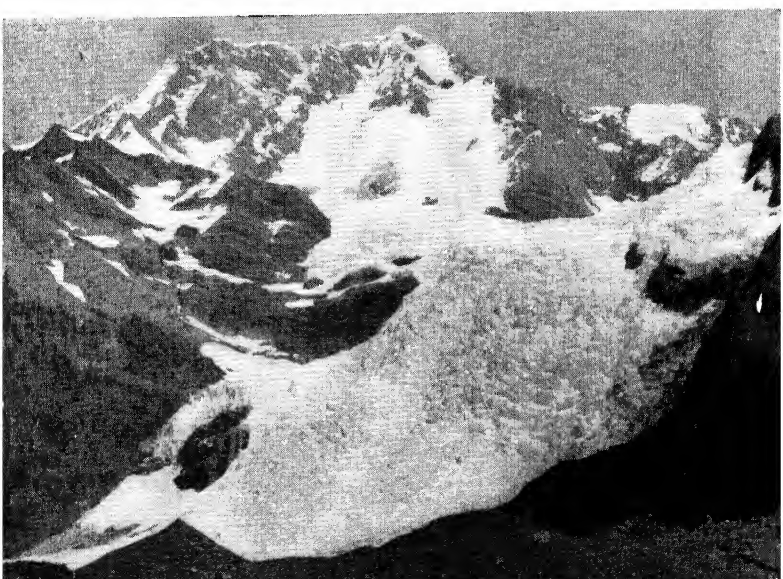
2. A glacier tongue, the Fox Glacier, New Zealand.

Plate XIII



F. G. Radcliffe, photo

1. Hanging glaciers on the face of Mt. Sefton, New Zealand. Avalanche ice from a glacier on a high shelf (at left) forms a reconstructed glacier on a lower shelf.



2. Ice-fall of the Hochstetter Glacier, Mt. Cook, New Zealand.

V. C. Browne, photo.

1. Longitudinal (radiating) tension cracks (due to spreading) and transverse crevasses on the Fox névé, New Zealand.

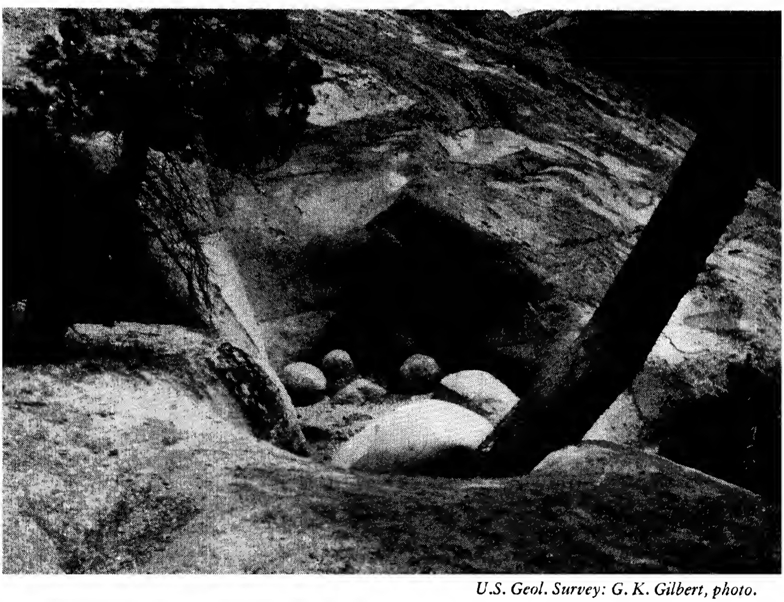
M. C. Lysons, photo.

Part of the chevron pattern of crevasses on the Franz Josef Glacier, New Zealand.

Plate XV

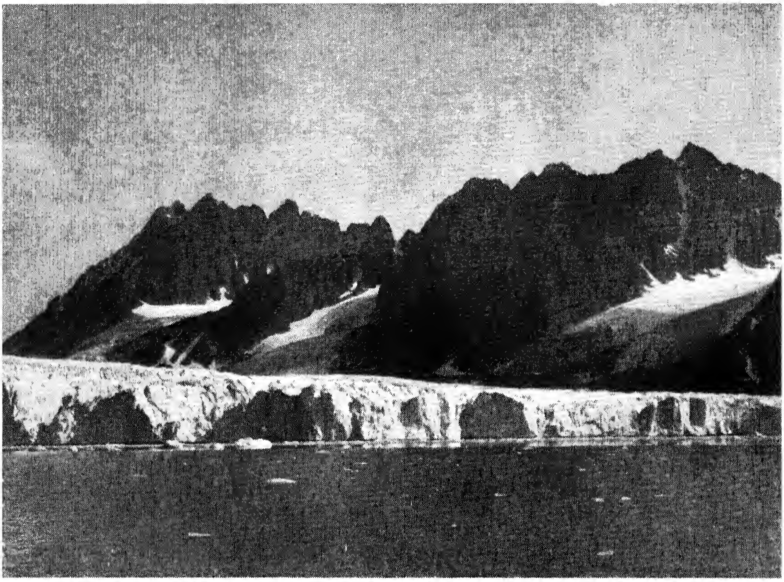
F. G. Radcliffe, photo

1. Details of the Hochstetter ice-fall, New Zealand, showing seracs.

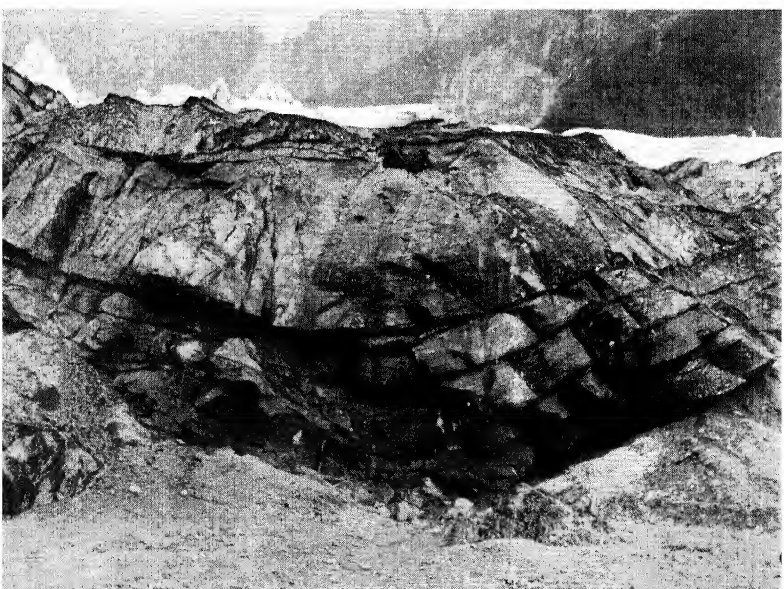


U.S. Geol. Survey: G. K. Gilbert, photo.

2. A moulin pothole, near Tuolumne Meadows, California. (Reproduced by permission.)

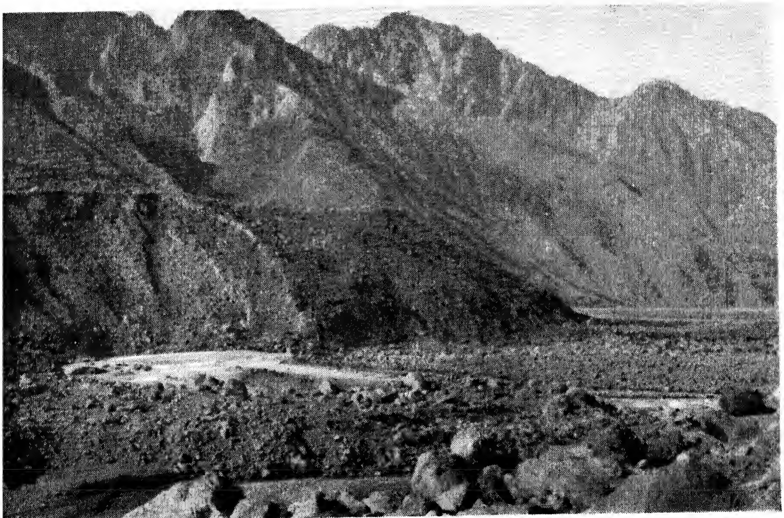


1. The terminal face of a tide-water glacier, Miller Fiord, Spitsbergen.



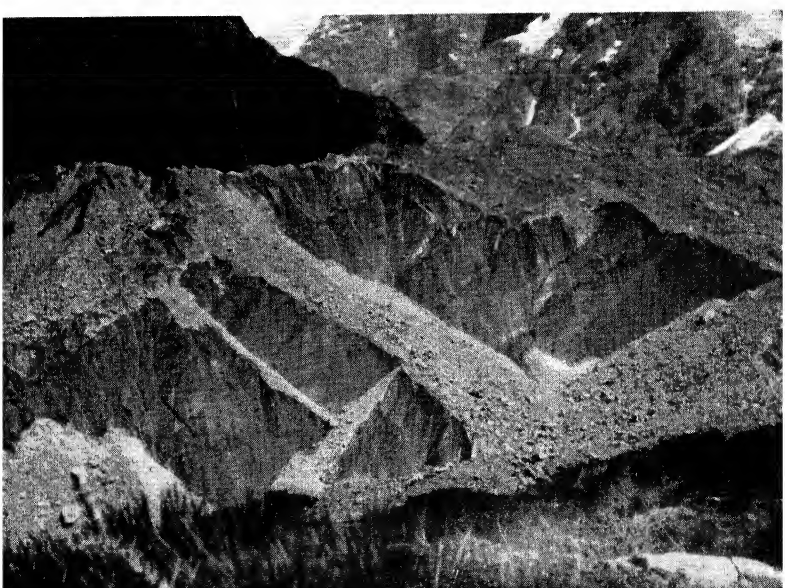
N.Z. Geol. Survey, photo.

2. The terminal face of the Franz Josef Glacier, New Zealand, showing thrust-planes in the ice.



Professor R. Speight, photo.

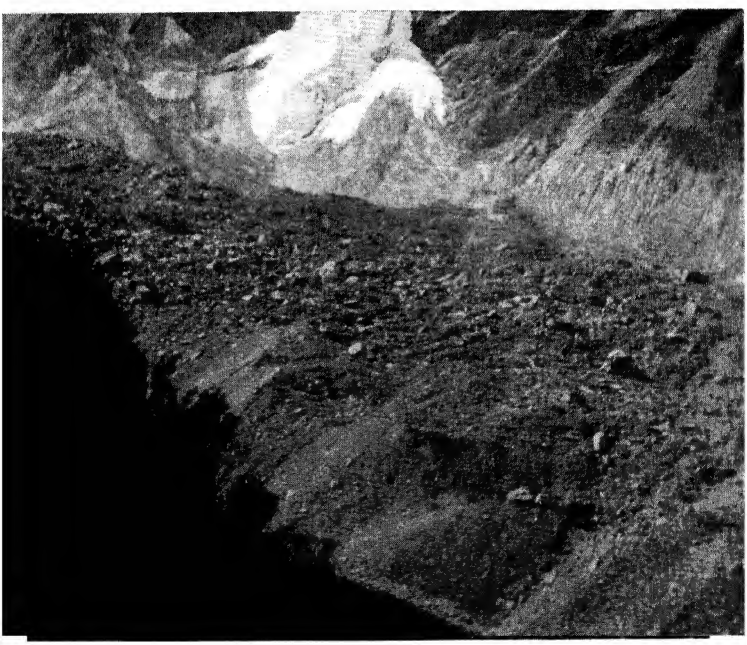
1. The terminal face of the Tasman Glacier, New Zealand, fully loaded with ablation moraine and englacial debris, which is supplied to and carried away by a large river of melt-water.



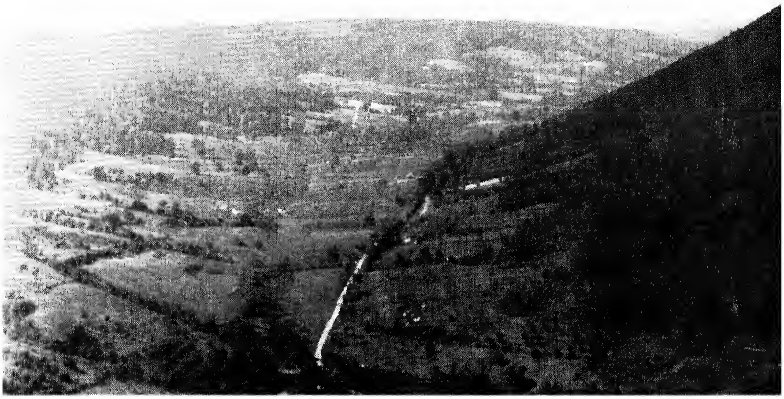
2. Englacial debris in the terminal face of the Mueller Glacier, New Zealand.

Plate XVIII

1. Screes of frost-riven rock descending to the Tasman Glacier, New Zealand.



2. Ablation moraine completely hides the ice of the Mueller Glacier, New Zealand.



Professor O. D. von Engeln, photo.

1. A grooved upland developed under an ice sheet, New York State.

Valentine, photo.

2. A catenary valley form, Glen Dogharty, Ross-shire, Scotland.

U.S. Geol. Survey: G. K. Gilbert, photo.

Glacial cirque, Darwin Canyon, Sierra Nevada, California, showing a schrund line. Cirque walls intersect to form arêtes; some convex summit forms survive. (Reproduced by permission.)

U.S. Geol. Survey: G. K. Gilbert, photo.

2. Cirques and a glacially-excavated valley floor on which are rock-rimmed and moraine-dammed lakes, Sierra Nevada, California. (Reproduced by permission.)

V. C. Browne, photo

1. The fretted upland of the St. Arnaud Range, Nelson, New Zealand. Lower slopes are not glaciated.

2. A fretted upland in the European Alps (Dent du Géant). *Swissair, photo.*

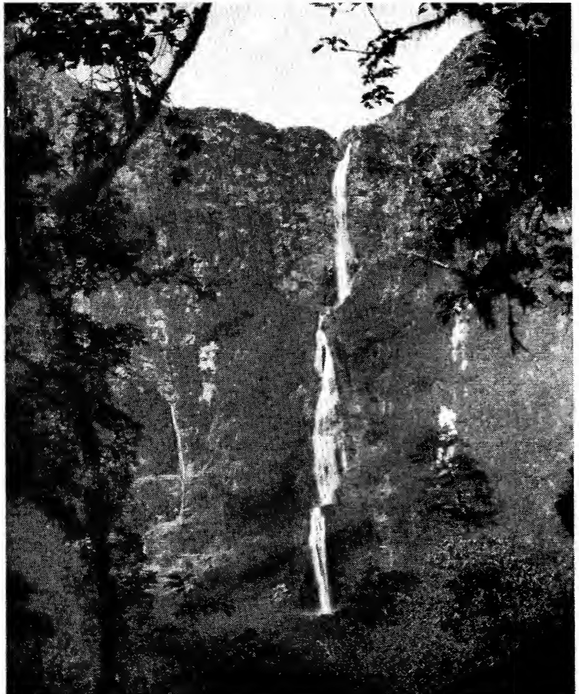
Plate XXII

H.M. Geol. Survey, photo.

1. A glaciated hanging valley entering Glen Lyon, Perthshire, Scotland. (Reproduced by permission.)

V. C. Browne, photo.

2. The 4000-feet-high wall of Milford Sound, a New Zealand fiord, with the Stirling Falls pouring from the mouth of a hanging valley 500 feet above sea-level.



H. C. Peart, photo.

1. The Sutherland Falls, 1904 feet, Fiordland, New Zealand, spill over the lip of the Lake Quill hanging valley (an enlarged cirque).

V. C. Browne, photo.

2. The Sutherland Falls and Lake Quill from above.

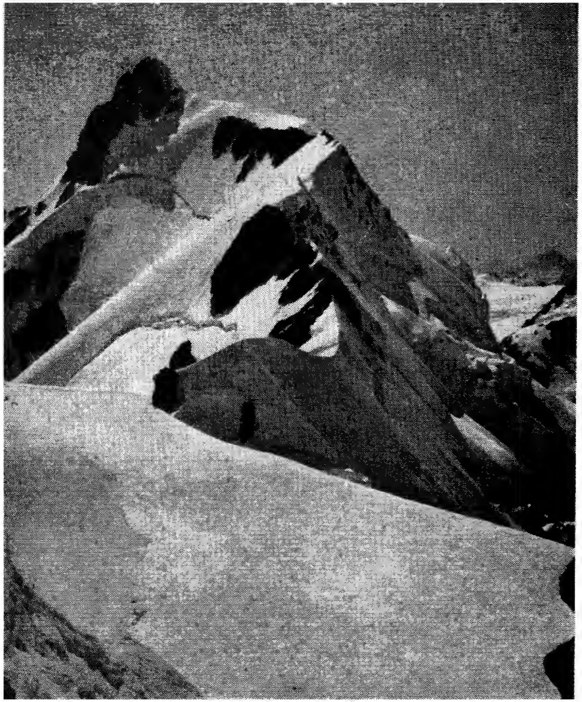
H.M. Geol. Survey, photo.

1. Intersection of concave cirque-wall slope with convex summit, Ben Nevis, Scotland. (Reproduced by permission.)

Reed's Ltd., Penrith, photo.

2. A great cirque in the flank of High Street mountain, Cumberland. It contains the rock-basin lake **Bleawater.**

Plate XXV



M. C. Lysons, photo.

1. "Bergschrund" crevasses in the snow-covered névé below an arête leading up to Mt. Haidinger, New Zealand.

V. C. Browne, photo.

2. Incipient secondary cirques fretting the summit of Mitre Peak, New Zealand. Lower slopes are broken by trough-in-trough shoulders.

Plate XXVI

H.M. Geol. Survey, photo.

1. An ice-smoothed armchair corrie, Ben Nevis, Scotland. (Reproduced by permission.)

U.S. Geol. Survey: G. K. Gilbert, photo.

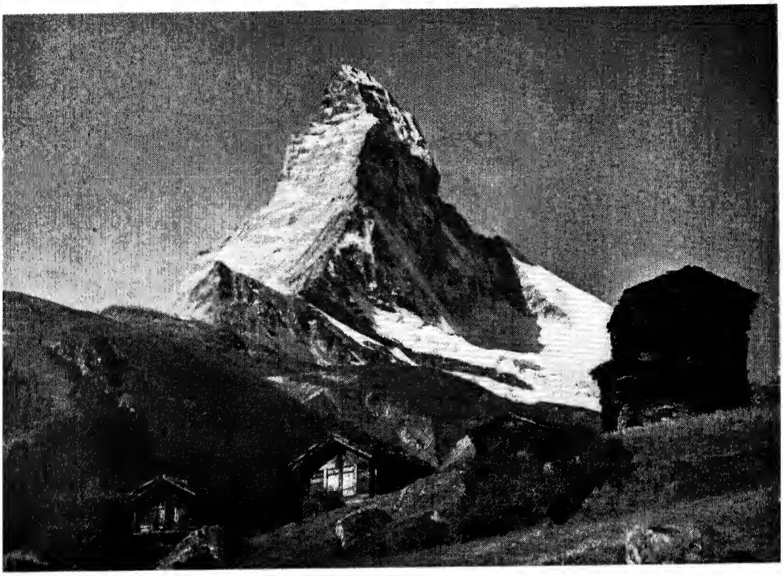
2. Strongly asymmetrical crest-lines formed by intersecting cirque walls (illustrating Gilbert's "systematic asymmetry") in the Sierra Nevada, California. (Reproduced by permission.)

V. C. Browne, photo.

1. Arêtes sharpened by cirque-wall sapping overlooking Sutherland Sound, Fiordland, New Zealand.

U.S. Geol. Survey: G. K. Gilbert, photo.

2. Cirques, arêtes, and a summit remnant of a preglacial land surface, Mt. Darwin, Sierra Nevada, California. (Reproduced by permission.)

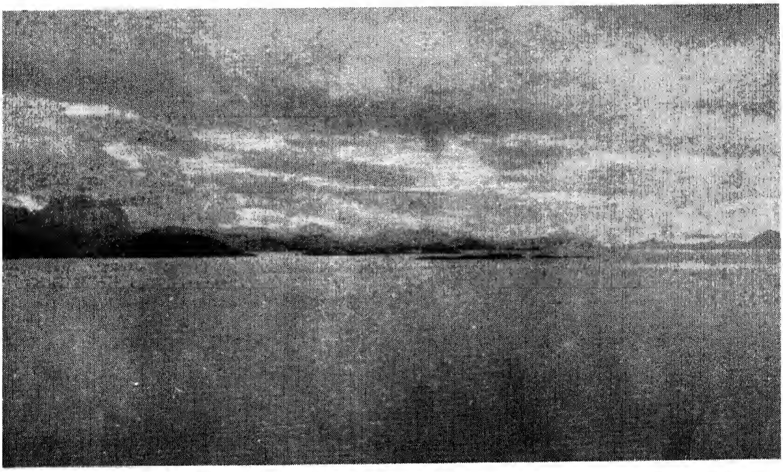


Gyger, phot

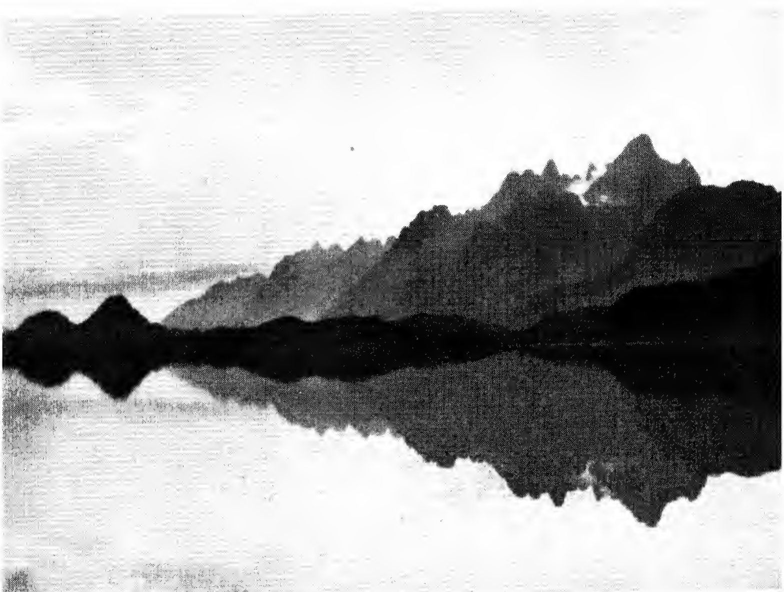
1. The Matterhorn, Switzerland.

M. C. Lysons, photo.

2. Horn and arêtes, Mt. Cook, New Zealand.



1. Skerries of the submerged strandflat, north-west coast of Norway.



Mittet, photo.

2. The Norwegian strandflat, Raftsund, Norway.

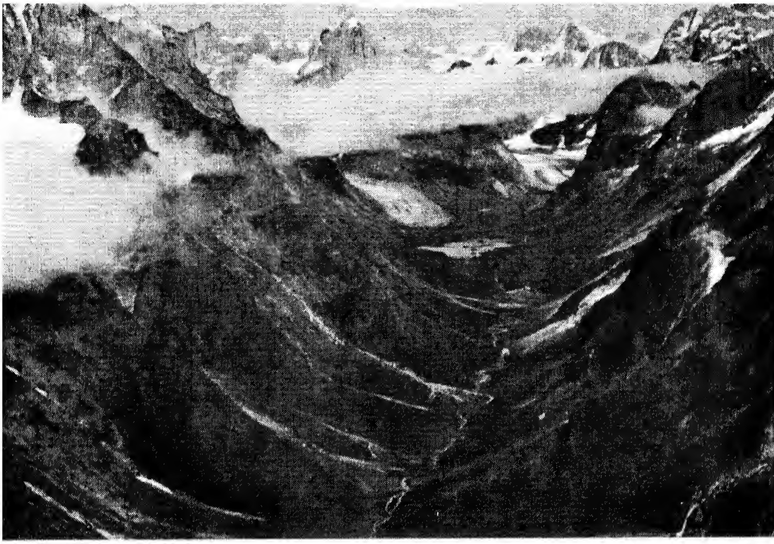
V. C. Browne, photo

1. A col worn down to U form by glacial transfluence, Arthur Pass, New Zealand.

M. C. Lysons, photo

2. A deeply-excavated trough which is still the channel of a glacier tongue, Franz Josef Glacier, New Zealand.

Plate XXXI



National Geographic Society: Charles and Anne Lindbergh, photo.

1. A U-form glacial trough in southernmost Greenland. (Reproduced by permission.)

Dr. C. O. Hutton, photo.

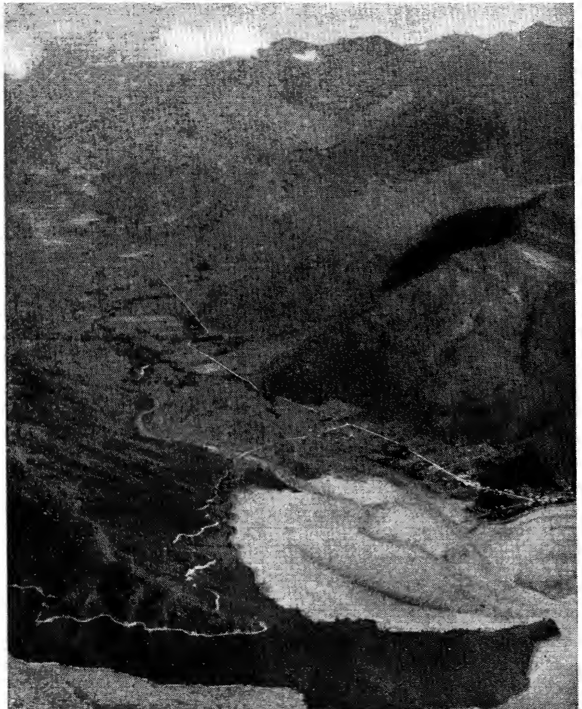
2. The broadly U-form (catenary) trough (mainly in schist terrain) of Mararoa Valley, containing the Mavora Lakes, Otago, New Zealand.

H.M. Geol. Survey, photo.

1. A gorge-like U-form trough developed locally across a bar of granite between areas of schist terrain, outlet of Lake Ossian, Scotland. (Reproduced by permission.)

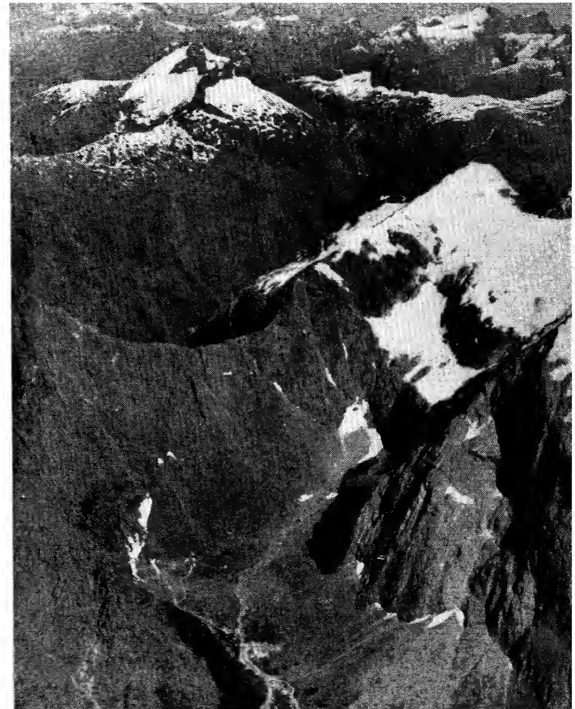
V. C. Browne, photo.

2. Y valleys dissecting the eastern side-wall of the catenary trough in schist terrain occupied by the upper reach (North Arm) of Lake Wakatipu, New Zealand.



V. C. Browne, photo.

1. A non-glaciated (river-made) trough valley with faceted side wall, Pelorus Valley, Marlborough, New Zealand.



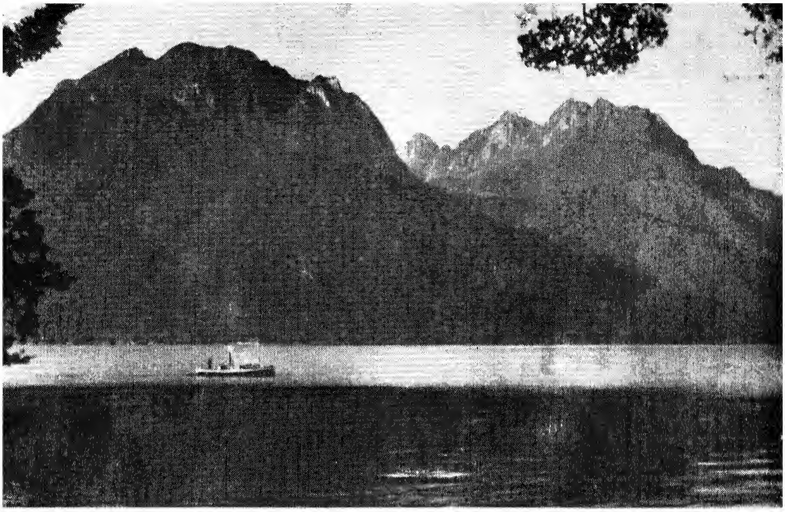
V. C. Browne, photo.

2. Troughs in Fiordland, New Zealand, at the main divide (Homer Saddle).

1. Hanging valleys still occupied by glaciers at Magdalen Bay, Spitsbergen.

2. Sinbad Valley, a large cirque-headed valley which hangs high above the deeply submerged fiord floor of Milford Sound beside Mitre Peak, Fiordland, New Zealand.

Plate XXXV



1. A glaciated hanging valley, Lake Manapouri, New Zealand.

Wehrli, photo.

2. The Rhone Glacier, Switzerland, spills out of the mouth of a hanging valley.

Professor R. Speight, photo.

1. A cirque enlarged to form a hanging valley on the wall of the Rangitata Valley, Canterbury, New Zealand.

R. S. Tarr, photo.

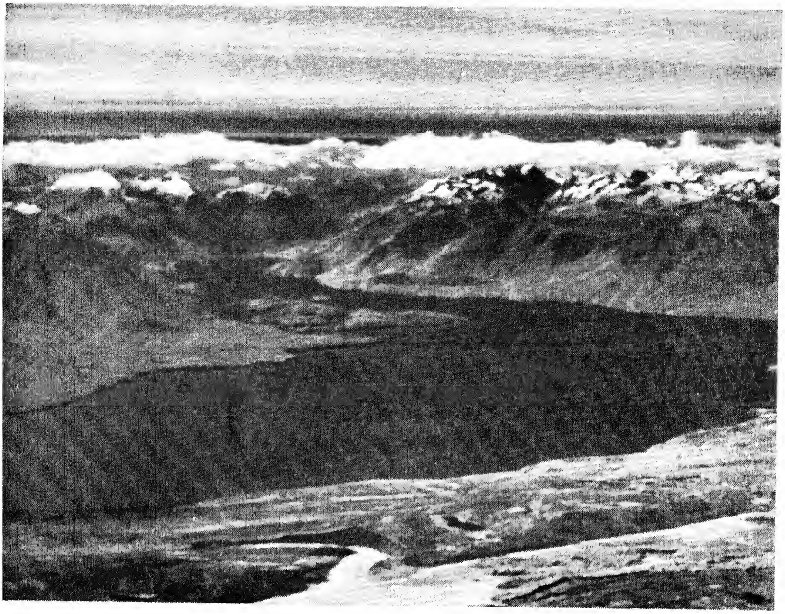
2. A bastion in front of the Cascading Glacier, Yakutat Bay, Alaska. (Reproduced by permission of Professor O. D. von Engeln.)

V. C. Browne, photo.

1. A mock hanging valley, in New Zealand, due to glacial diffluence. A distributary glacier entered the Greenstone Valley (left), branching from the trough of the Eglinton-Hollyford "through" glacier.

Swissair, photo.

2. The Unteraar Glacier, Switzerland, occupying a deeply-excavated trough which swings in curves of wide radius.



V. C. Browne, photo.

1. A basal remnant of a truncated spur at the junction of the Middle Fiord arm of Lake Te Anau, New Zealand, with the main trough.

2. A knob field on the site of a glacially truncated spur, west side of Lake Wanaka, New Zealand.

Professor R. Speight, photo.

1. The basal remnant of an incompletely truncated spur surviving as a semi-detached knob, Waimakariri Valley, New Zealand.

Carl Normann, photo.

2. A giant sugarloaf form carved from an overridden valley-side spur at a glacial confluence, Nærodal trough, Norway.

Plate XL

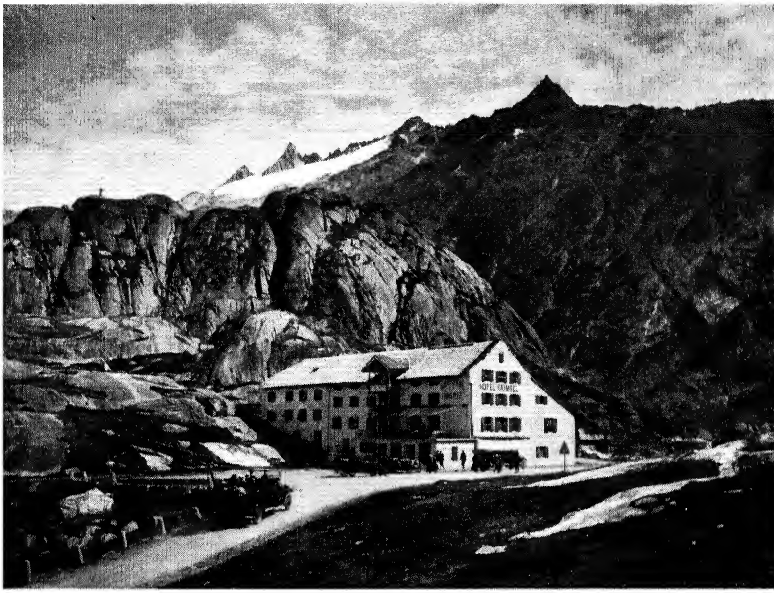
H.M. Geol. Survey, photo.

1. Roche moutonnée and ice-scoured rock surface, Inverness-shire, Scotland. (Reproduced by permission.)

U.S. Geol. Survey: G. K. Gilbert, photo.

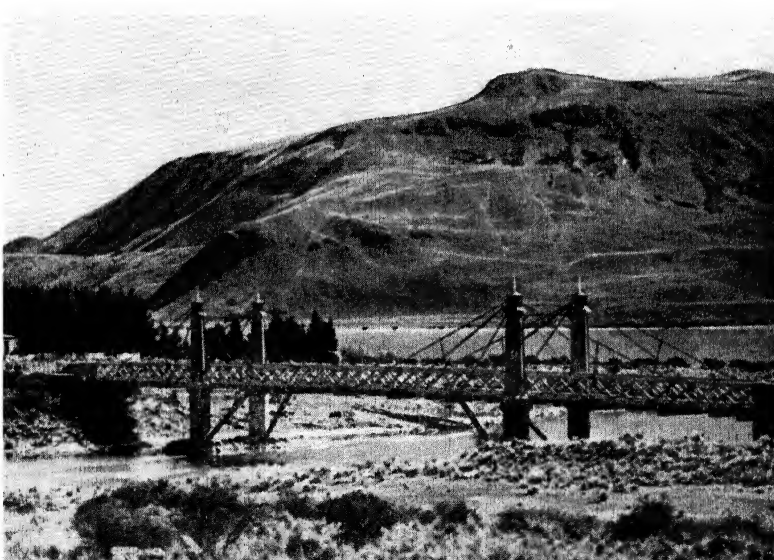
2. A roche moutonnée, South Fork, San Joaquin River, Sierra Nevada, California. (Reproduced by permission.)

Plate XLI



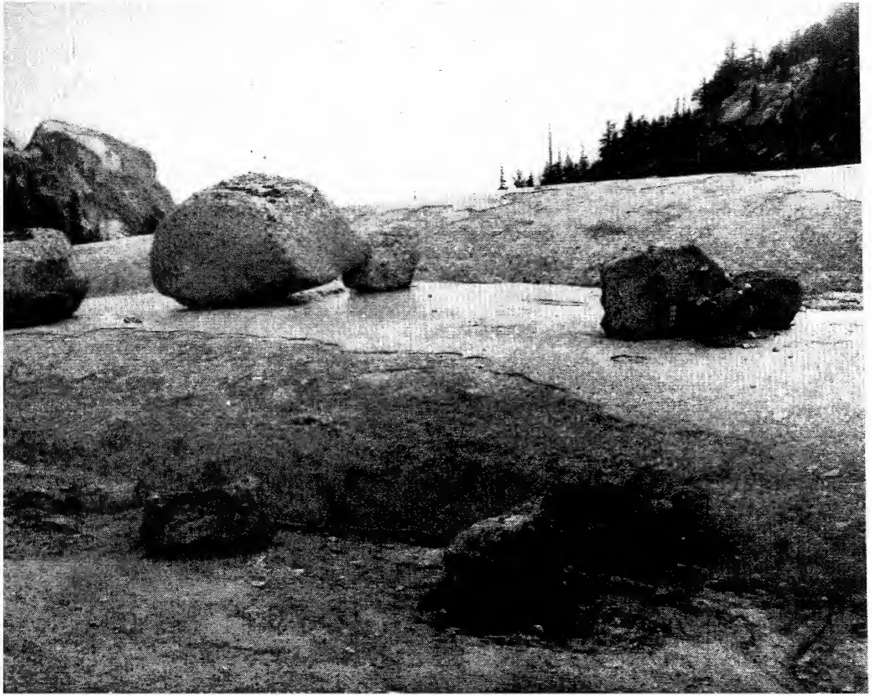
J. Gaberell, photo.

1. Mammillated rock surface and giant roche moutonnée, Grimsel Pass, Switzerland.



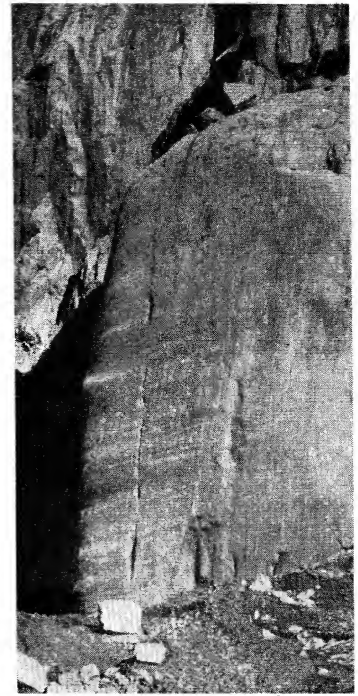
Rose, photo.

2. An ice-shorn hill with plucked lee slope, beside Lake Tekapo, New Zealand.



Professor Eliot Blackwelder, photo.

1. Perched blocks on a glacially-polished rock floor, Sierra Nevada, California.



M. C. Lysons, photo.

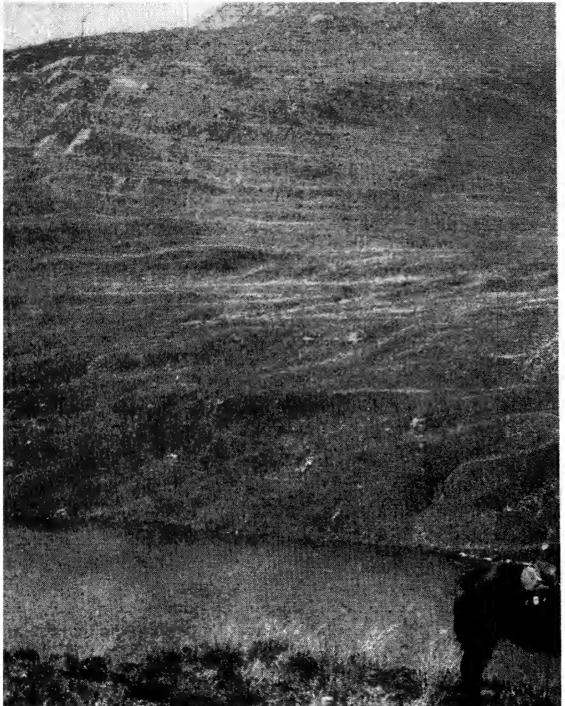
Polish and striation resulting from glacial abrasion on the nearly vertical side wall of the Fox Glacier **trough, New Zealand.**

J. Gaberell, photo.

1. A mammillated bench above a trough-side shoulder, Gornergrat, Switzerland.

V. C. Browne, photo.

2. A mammillated surface on schist terrain, Peninsula Hill, Queenstown, New Zealand.



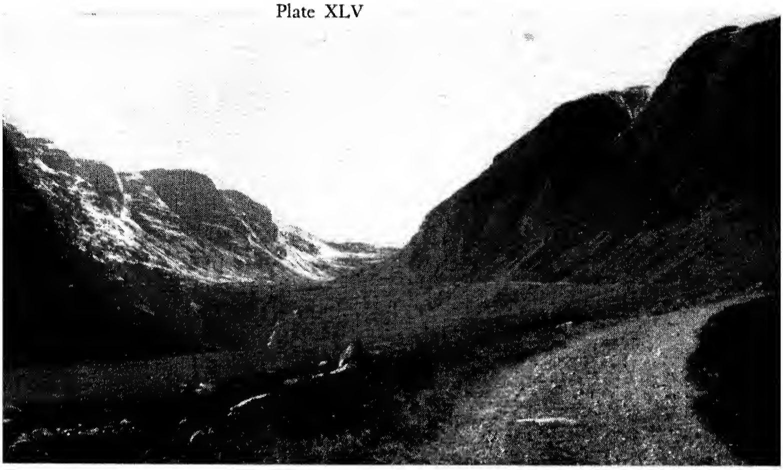
Professor James Park, photo.

1. Structurally controlled glacial groove-and-bench terraces in the schist terrain, Lake Luna, Otago, New Zealand.

V. C. Browne, photo.

2. Irregular terraces resulting from structural control of glacial erosion, east side of Lake Wakatipu trough, New Zealand.

Plate XLV



H.M. Geol. Survey, photo

1. A step on the floor of a small glacial trough in Torridon Sandstone terrain, Coire na Ba, Applecross, Ross-shire, Scotland. (Reproduced by permission.)

M. C. Lysons, photo.

2. A step on the valley floor of a tributary of Arthur Valley, Fiordland, New Zealand.

V. C. Browne, photo.

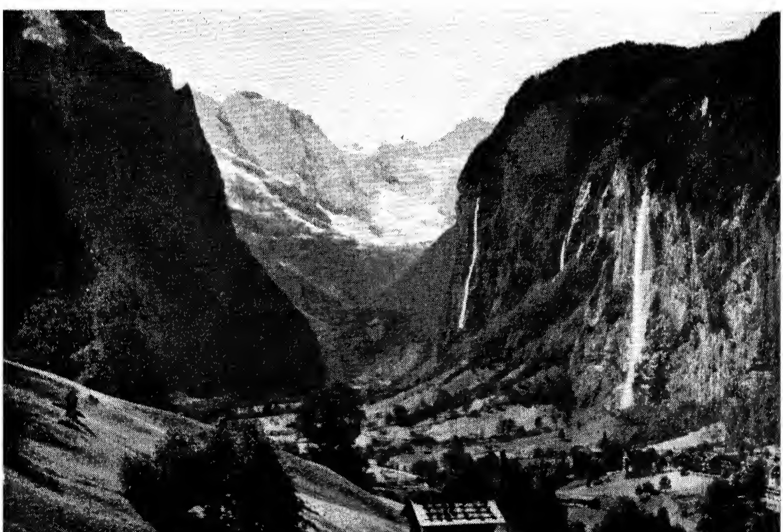
1. A gigantic worn-down "ex-riegel" in the Hollyford-McKerrow glacial trough, Fiordland, New Zealand.

Dr. C. O. Hutton, photo.

2. Part of the great trough occupied by Lake Wakatipu, New Zealand. In the lower reach, or South Arm (at left), is the deepest part of the lake (1242 feet).

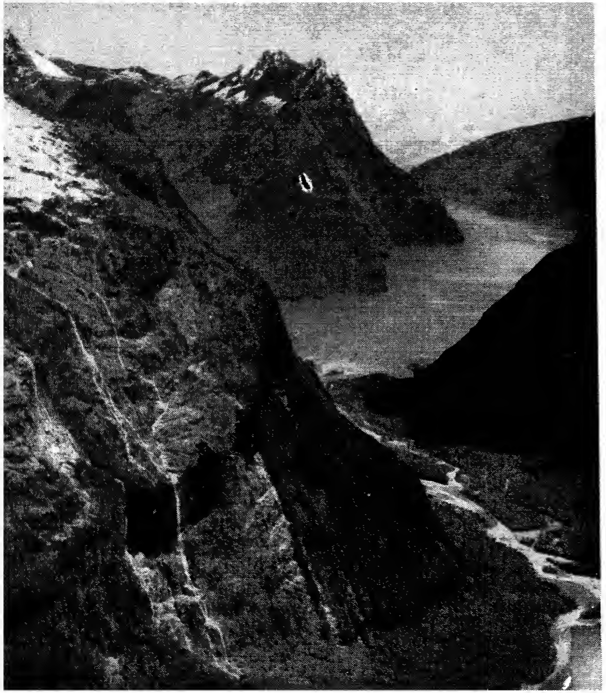
Wilse, photo.

1. Geiranger Fiord, Norway. The Seven Sisters waterfalls descend over a bastion from a hanging valley. The fiord wall is abraded and mammillated.



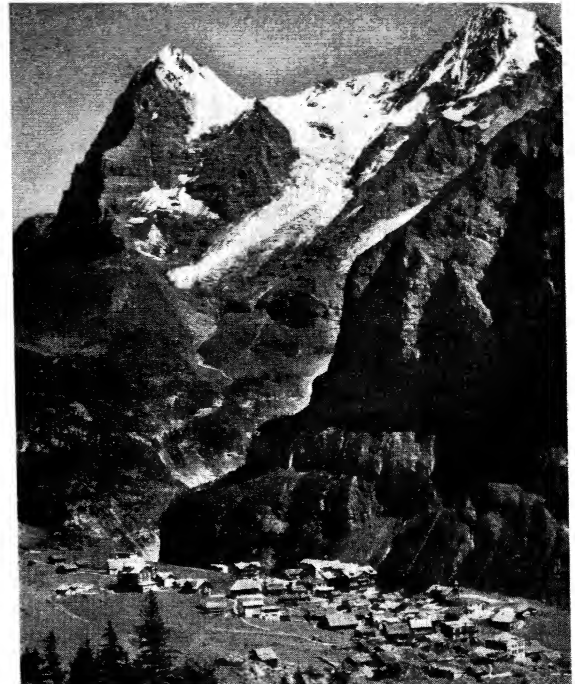
Wehrli, photo.

2. The Lauterbrunnen trough and shoulder of the Mürren-Grütschalp bench, Switzerland.



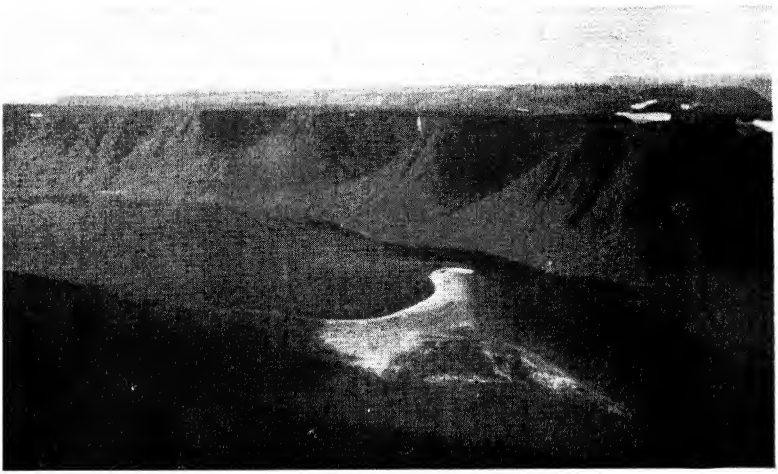
V. C. Browne, photo.

1. Milford Sound, Fiordland, New Zealand. Several shoulders on Mt. Sheerdown (left) and in the lower reach of the fiord (distance) suggest trough-in-trough forms.



Wehrli, photo.

2. "Architectural" shouldered slopes of the Jungfrau group with the Mürren-Grütschalp bench (XLVII, 2), seen from above, in the foreground. The bench is 2000 feet above the floor of the Lauterbrunnen trough.



National Geographic Society: Charles and Anne Lindbergh, photo.

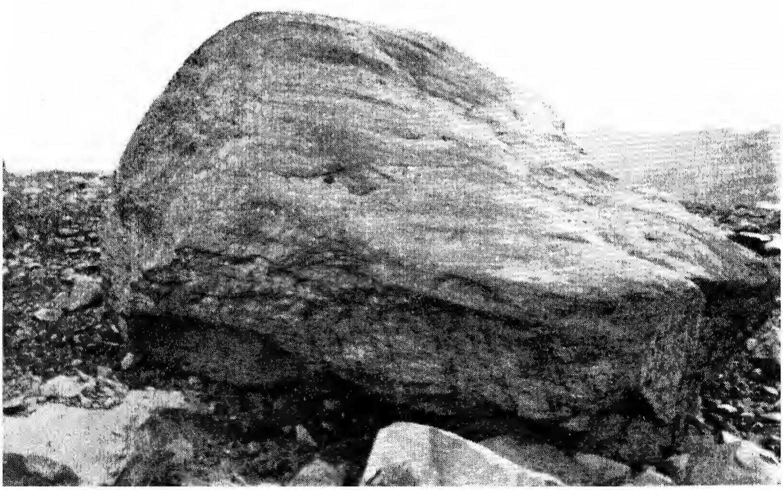
1. Glaciated trough and cirques excavated in the lava-built plateau of north-western Iceland. (Reproduced by permission.)

R. W. Willett, photo.

2. Structurally controlled, glaciated benches, east side of Rees Valley trough, north-western Otago, New Zealand. There has been deep postglacial dissection.

Plate L

1. An erratic block carried by the former Lake Wakatipu glacier and deposited near Arrowtown, New Zealand.

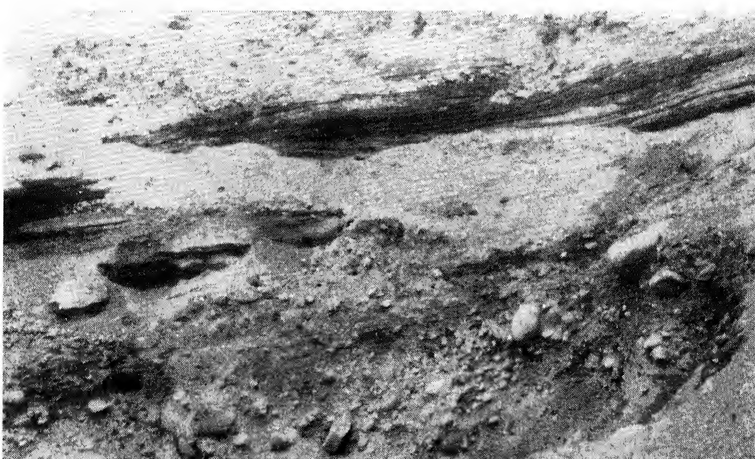


Professor O. D. von Engeln, photo.

2. An unusually large shaped ("flat-iron") glacial boulder, Norway.

G. K. Gilbert, photo.

1. Glacial boulder clay (till) overlying an abraded and scored rock surface, east shore of Lake Erie, North America. Irregular scorings that cross the regular parallel striae were added by iceberg-borne rock fragments.

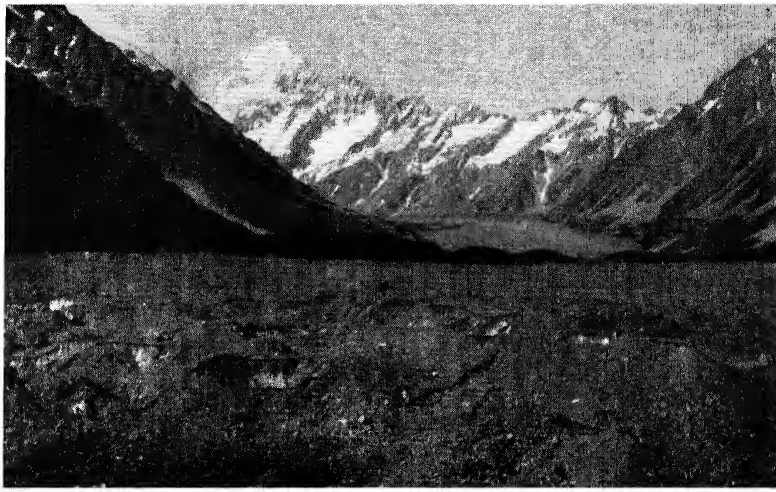


2. Ground moraine underlying stratified fluvioglacial sand and gravel, Lake Monowai, New Zealand.

H.M. Geol. Survey, photo.

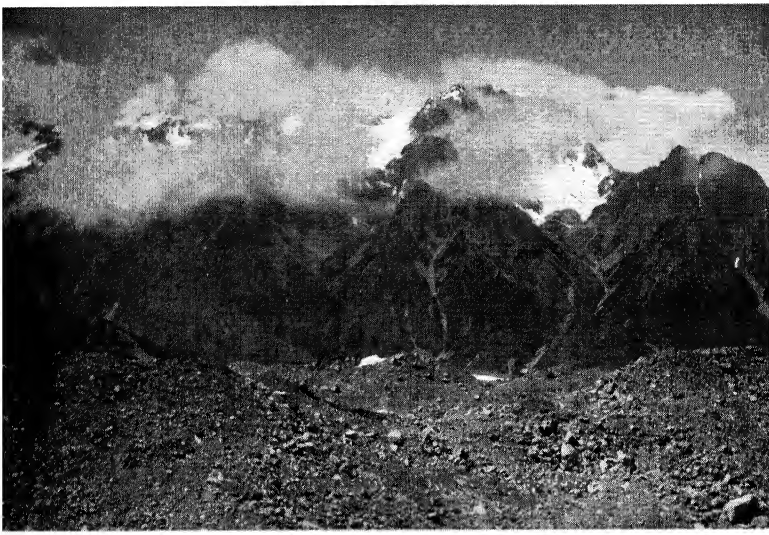
1. Hummocky (knob-and-kettle) end moraines, Fannich Forest, Ross-shire, Scotland. (Reproduced by permission.)

2. Terminal moraines trenched by a river of melt-water near the terminus of the Hooker Glacier, New Zealand.



1. In the distance, at the base of Mt. Cook, is a terrace of stranded lateral moraine bordering the Hooker Glacier. Nearer at hand, nearly hidden by ablation moraine and bounded by a moraine loop, is the ice of the Mueller Glacier (New Zealand).

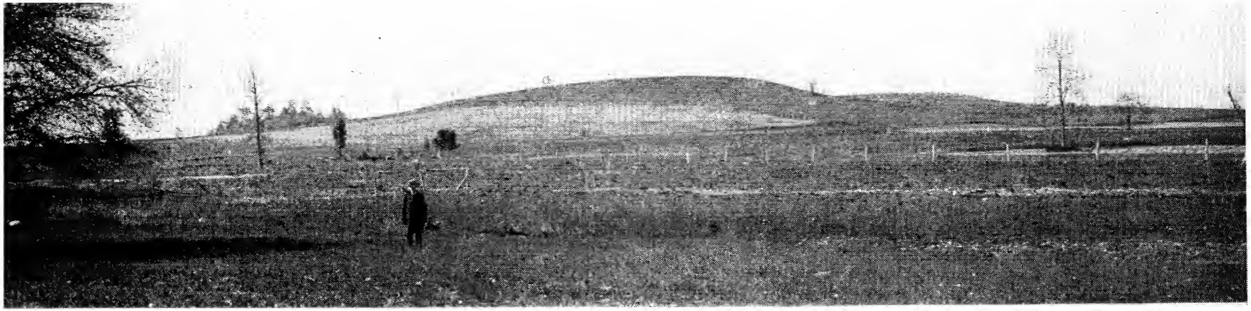
2. Stranded lateral moraine of the Hooker Glacier, New Zealand.



F. G. Radcliffe, photo.

1. A broad hummocky belt of stranded lateral moraine beside the Tasman Glacier, opposite the Liebig Range, New Zealand.

2. Part of the moraine loop around the terminus of the Mueller Glacier, New Zealand.



1. A drumlin south of Newark, New York. (Reproduced by permission.) *U.S. Geol. Survey: G. K. Gilbert, photo.*

2. Valley trains of the Hooker (left) and Tasman Glaciers, New Zealand. *Mrs. Peter Graham, photo.*

Plate LVI

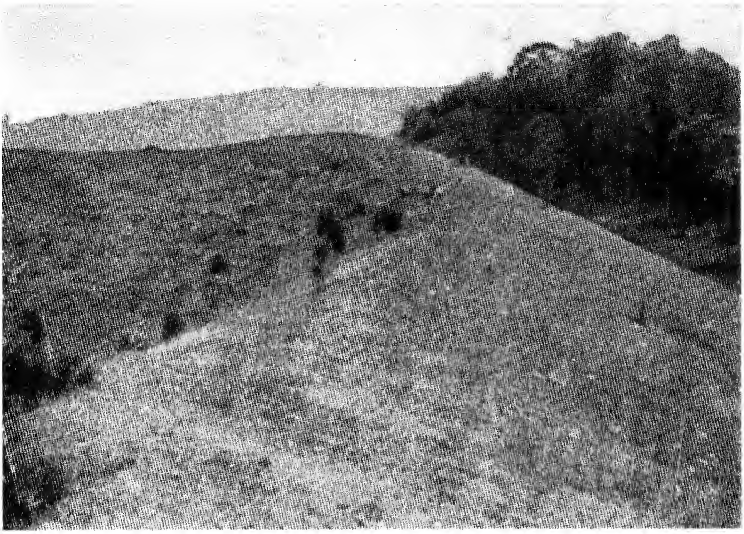
Professor R. F. Flint, photo.

1. A fluvially deposited kame terrace with an ice-contact face, Colebrook, Connecticut.

Professor R. F. Flint, photo.

2. Kettles in an ice-contact mass of sand and gravel, Portland, Connecticut.

Plate LVII



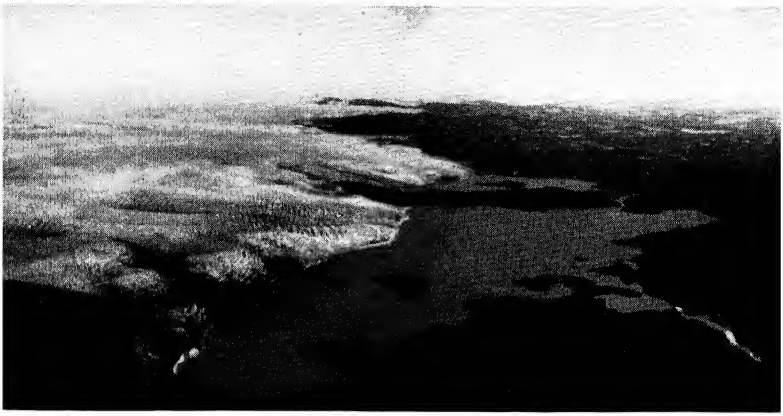
Professor J. L. Rich, photo.

1. An esker in the Catskill Mountains, New York. (Reproduced by permission of the New York State Museum.)

H.M. Geol. Survey, photo.

2. Parallel Roads, Glen Roy, Scotland. Shoreline terraces of a proglacial lake. (Reproduced by permission.)

Plate LVIII



National Geographic Society: Charles and Anne Lindbergh, photo.

1. A proglacial lake marginal to the Greenland ice sheet. (Reproduced by permission.)

Professor O. D. von Engeln, photo.

2. A stream marginal to the Variegated Glacier, Alaska, flowing between the glacier (left) and a mountain spur, in the bedrock of which rapid excavation of a stream-cut trench is in progress.

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CHRISTCHURCH AUCKLAND
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